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Material Signals: A Historical Sociology of High-Frequency Trading[1]

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Drawing on interviews with 194 market participants (including 54 practitioners of high-frequency trading or HFT), this article first identifies the main classes of "signals" (patterns of data) that influence how HFT algorithms buy and sell shares and interact with each other. Second, it investigates historically the processes that have led to three of the most important categories of these signals, finding that they arise from three features of U.S. share trading that are the result of episodes of meso-level conflict. Third, the article demonstrates the contingency of these features by briefly comparing HFT in share trading to HFT in futures, Treasurys, and foreign exchange. The article thus argues that how HFT algorithms act and interact is a specific, contingent product not just of the current but also of the past interaction of people, organizations, algorithms, and machines.

INTRODUCTION

Until the mid-1990s, almost all U.S. share trading required direct human involvement, usually via telephone calls or on crowded trading floors. Now, it mostly takes place in five large computer data centers in New Jersey (see fig. 1), each almost devoid of human beings and packed instead with tens of thousands of servers interconnected by a vast spider's web of cables

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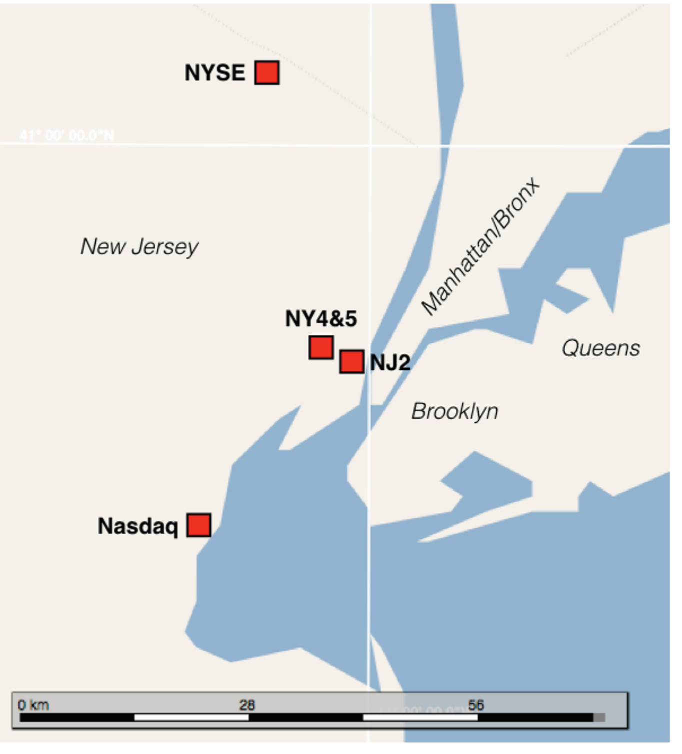


FIG. 1.—The five main U.S. share trading data centers. NY4 and NY5 (in Secaucus) and NJ2 (in Weehawken) host multiple trading venues; the NYSE and Nasdaq data centers host the main computer systems of those exchanges.

and switches. Massive volumes of messages—a million per second is routine—flow through these webs, as well as among the five data centers via fiber-optic cables and millimeter wave links.[2] Lasers, originally designed for military use, flash signals (not usually visible from the ground) from data center to data center across the skies of northern New Jersey. Transmission times between data centers are now within a few millionths of a second of what the theory of relativity posits as the fastest physically possible.

Much of the flow of messages is the result of bids to buy shares or offers to sell them (or cancellations of bids or offers), entered not by human beings but by computer algorithms. Some of the latter—known as "execution algorithms"—take a "parent" order from an institutional investor to buy or to sell a large block of shares and break it up for less easily detectable execution

[2] On December 7, 2016, data vendor Exegy recorded a peak flow of 10.6 million messages a second in one of the data centers, NY4. See https://www.marketdatapeaks.com/.

into multiple small "child" orders. Others are high-frequency trading or HFT algorithms. HFT is proprietary trading (i.e., the pursuit of trading profits rather than earning fees for executing others' orders) that is fully automated and ultrafast and usually involves very large numbers of individually small trades.

HFT firms are mostly highly specialized, and nearly all are recently established and quite small; big banks are not prominent in HFT, especially since the postcrisis curbs on their proprietary trading. Although publicly available data do not reveal whether any given order is placed by a human being or an algorithm, most observers agree that around half of all purchases and sales of U.S. shares are made by HFT algorithms (see, e.g., Meyer, Massoudi, and Stafford 2015), and a substantial further proportion, of which there are no consensual estimates, is accounted for by other types of algorithms. The direct interaction of human beings in U.S. share trading has thus largely been replaced by what Knorr Cetina (2013) in a talk at the American Sociological Association's annual meeting christened "the interaction order of algorithms."[3]

The research reported here had three overlapping aspects. First, I interviewed 54 high-frequency traders, seeking as in-depth an understanding of HFT practices as possible. Unsurprisingly, interviewees did not usually disclose details of what they often call "secret sauce"—private, proprietary knowledge—and I did not probe for those details. Nevertheless, many interviewees were prepared to talk about common HFT practices, and some described their secret sauce in general terms. Among the topics explored in the interviews was what practitioners of HFT call "signals": patterns in the data received by their algorithms that affect how those algorithms behave, in particular, by prompting them to place an order to buy or to sell shares, or to cancel an earlier order. (In this article, the term "algorithm" is used in the way participants use it—to refer not just to a set of instructions sufficiently precise that they can be encoded in a computer program but also to that program running on a physical computer system and having effects on other

[3] There is the beginnings of a sociological literature on HFT, albeit one that has not tackled this article's focus: the signals employed by HFT algorithms. Perhaps closest to this article's concerns are the examinations of "spoofing" (see below) in Arnoldi (2016) and the discussion in Borch (2016) of analyses of the May 2010 U.S. stock market "flash crash" that postulate "herd behavior" by algorithms. Other important contributions include the studies by Borch, Hansen, and Lange (2015), who apply Lefebvre's rhythmanalysis to the role of traders' bodies in HFT, contrasting it with bodily rhythms on trading floors; Borch and Lange (2016), who examine high-frequency traders' subjectivity; and Seyfert (2016), who discusses the different sense-making regimes via which unusual trading patterns are interpreted by high-frequency traders, their critics, and market regulators. Also of relevance, although not focused directly on HFT practices, are the discussions of regulation in Lenglet (2011), Castelle et al. (2016), Coombs (2016), and Lenglet and Mol (2016).

systems.) In the market focused on in this article (U.S. shares), the interviews reveal four classes of signals that are widely used by HFT algorithms, along with two further classes that are in more restricted use and one class that was of historical importance to the emergence of HFT but no longer exists (see table 1).

Second, I investigated historically what brought these classes of signals into being. While the fourth of the four main classes of signal involves processes of a different kind that cannot be discussed for reasons of space,[4] the other three turned out all to involve specific features of how U.S. shares are traded: first, the differences between how futures on share indices are traded and how shares themselves are traded; second, the creation of "order books" of unexecuted orders, and the dissemination of those "books" to market participants, both human and algorithmic; and third, the fragmentation of share trading across multiple venues. Those three features are not the inevitable products of automation, but the outcome of meso-level conflicts—the first and third with origins in the 1970s and the second in the 1990s—over where and how U.S. shares (and futures) should be traded. This article's subtitle, "A Historical Sociology . . . ," refers to its excavation of these conflicts.

Third, the research examined not just shares but also the trading of futures and Treasurys (U.S. federal government securities), which are markets in which HFT is a major presence, along with a number of other markets in which it has so far been less successful, of which the most important is "spot" (near-immediate delivery) foreign exchange (see table 2). The examination of these other markets is not a formal comparative analysis: there are too many variables and too few cases, and the latter are too interwoven. Rather, those other markets are touched on briefly here to demonstrate the specificity and contingency of how U.S. shares are traded and thus to show that the conflicts that have shaped share trading are more than its now-irrelevant past.

This threefold analysis brings together two strands within economic sociology that are ordinarily thought of as different, even in conflict. One is Callon and Latour's actor-network theory, which emphasizes the role of technologies and other nonhuman entities in social relations, even being prepared to entertain the classification of such entities as "actors" (see, e.g., Latour 2005). Clearly, a case can be made for calling an algorithm that makes share-trading decisions without direct human involvement an actor, but whether or not to do so is a red herring here: it depends on what one means by "action" and "agency." Rather, what is needed from actor-network

[4] It involves the classification of firms into economic sectors: an example is the correlation between the share prices of two corporations viewed by market participants as exposed to the same underlying economic factors. For sociological analyses of the classification of firms, see Zuckerman (1999, 2000) and Beunza and Garud (2007).

TABLE 1
The Main Classes of Signals Employed in HFT in U.S. Shares

Classes of Signals	Signals
Widely used:	
Futures lead	Changes in market for share-index futures (which usually slightly precede changes in the market in the underlying shares)
Order book dynamics	Transactions in the shares being traded and other changes in the "order book" for them on the venue on which an algorithm is trading, e.g., changes in the balance of bids to buy and offers to sell
Fragmentation	Transactions in or changes in the order books for the same shares on different trading venues
Related shares and other instruments	Changes in the market for, e.g., shares whose price is correlated with that of the shares being traded
Specialized classes:	
News	Machine-readable corporate or macroeconomic news releases
Stale midpoint matching	Out-of-date prices being used in the execution of transactions at the midpoint of the highest bid price and lowest offer price
No longer extant class:	
SOES banditry	Repricing of bids and offers by Nasdaq's official market makers (e.g., because they were executing a large institutional investor order)

Note.—A "signal" is a data pattern that informs an algorithm's trading. This article examines the uses by HFT algorithms of the first three of these classes of signal, the material forms those signals take, and the processes that have given rise to them. SOES was Nasdaq's Small Order Execution System (see the section HFT and the Transformation of Share Trading).

TABLE 2
Rough Estimates of the HFT Share of Trading Volumes

	Estimated Share
U.S. shares[a]	Around half
U.S. futures[a]	Around half
Benchmark U.S. Treasurys[b]	Around half
Nonbenchmark Treasurys[b]	Little HFT
Spot foreign exchange[c]	Around a tenth

Note.—Only approximate figures are given, because publicly available quantitative data do not identify trading by HFT firms. The benchmark U.S. Treasurys are the most recently issued two-, three-, five-, seven-, and 10-year notes and 30-year bonds. Spot foreign exchange refers to transactions for near-immediate delivery.

[a] Miscellaneous sources (e.g., Meyer et al. 2015; Meyer and Bullock 2017).

[b] Michael Spencer, chief executive of ICAP (owner of BrokerTec trading platform), as quoted by Leising (2014); interviewee FO.

[c] Based on the volumes transacted by "hedge funds and PTFs [proprietary trading firms]," as reported by central banks to the Bank for International Settlements (2016, p. 13, table 5).

theory is its emphasis on materiality—on physicality, technicality, and embodiment (MacKenzie 2009)—and on how materiality is enacted. For example, Callon and those, such as the author, influenced by him have highlighted the pervasive role of "market devices" in economic life (see, e.g., Callon, Millo, and Muniesa 2007). While the word "device" hardly does justice to the huge, quicksilver, pulsating technological system just sketched, economic interaction in that system plainly takes a material form.

That materiality can loosely be called "Einsteinian": the materiality of a domain in which, as a result of how the practices of HFT have evolved, the speed of light has become a binding constraint. "Now you have to be under a microsecond," interviewee AG told me in October 2016: an HFT algorithm needs to respond to at least the simpler types of signal in less than a millionth of a second (this contrasts with my first interview with him, in December 2011, when a leisurely five-microsecond response was adequate). In a microsecond, light in a fiber-optic cable travels only around 200 meters; an electromagnetic signal transmitted through the atmosphere only 300 meters. Precise physical locations—of a computer server, a microwave or millimeter wave dish, or laser—are therefore exquisitely important and sometimes are the object of fierce competition. Nor is the material world simply what is struggled over. Rather, the very outcomes of struggles are influenced by the material circumstances in which they take place and by the material capacities that are brought to bear.

Actor-network inflected economic sociology remains controversial, however. It has been sharply criticized for neglecting issues of what might be called "political economy," such as "the effects of government and law and the role of pre-existing relationships" (Fligstein and Dauter 2007, p. 107; see also, e.g., Hardin and Rottinghaus [2015] and, more polemically, Mirowski and Nik-Khah [2007]). This article's historical sociology of HFT demonstrates effects of exactly the kind that Fligstein and Dauter point to. The signals that influence how algorithms trade are in good part the result of a succession of episodes of meso-level conflict about features of trading that gave some traders and some exchanges structural advantages—episodes in which government agencies were entangled and law was sometimes prominent.

As just suggested, the outcome of that succession of episodes reflects not only relationships directly among human beings but also—just as actor-network theory would predict—the lasting influences of technological choices and of the way in which algorithms alter the balance of power among human beings. However, the salience of meso-level conflict and of structural advantage suggests the need to complement the actor-network focus on materiality with a different perspective that highlights these aspects of economic life. Particularly useful for the analysis in this article is the theory of "fields," especially as developed by Fligstein and MacAdam (2012). For them, a field is a structured meso-level domain in which participants orient themselves to each other. There is "something at stake" (often something specific to the domain), differential access to resources, "rules of the game," and structurally more favorable (and less favorable) positions. There is cooperation, competition, and sometimes conflict, the last of these at least potentially involving challenges to the "rules of the game" (Kluttz and Fligstein 2016, p. 185). This view of fields builds directly on the sociology of markets, in particular as put forward in Fligstein (1996, 2001), and is among the versions of field theory that acknowledge path dependence in how fields develop: that, in the words of Martin's review of field theory, see social action as "saturated with history" (Martin 2003, p. 44).

Two immediate provisos are needed. First, to be applicable here, field theory needs to be given a more materialist twist than is common (although some field theorists, notably Bourdieu, are attentive to materiality; see, e.g., Bourdieu 1970, 1977). For example, as already indicated, the positions struggled over by HFT firms are physical locations, not just socioeconomic roles. Second, what follows is not a systematic field-theoretic analysis. Rather, field theory is invoked because it sensitizes us, much more directly than actor-network theory does, to four crucial issues.

Three of those issues (meso-level conflict, structural advantage, and path dependence) have already been touched on above. The fourth is another basic precept of modern sociological field theory: the outcomes of conflicts in a field typically depend on developments in adjacent fields (Fligstein and McAdam 2012, chap. 4). HFT is, plainly, a type of trading, and trading is clearly a field in which there is contestation, for profits and sometimes for legitimacy. Central to this article's analysis, however, is that the conflicts that have resulted in the signals available to HFT algorithms have overflowed the field of trading. Their outcomes have been influenced by developments in three other domains that can also be conceptualized as fields: exchanges, regulation, and politics (see fig. 2). Politics is also clearly a contested field, as are exchanges (competition for market share—and, again, sometimes also for legitimacy—is fierce). It is less obvious to think of regulation as a contested field (rather than simply a fixed external constraint on trading), but U.S. financial markets are characterized by the presence of multiple federal regulatory bodies (and even some state regulators, especially New York's, play significant roles). In particular, two federal regulators—the Securities

Fig. 2.—Four fields or "ecologies"

and Exchange Commission (SEC) and the Commodity Futures Trading Commission (CFTC)—have fought repeated "turf battles," and (as will be shown below) their split jurisdiction was the source of the historically primary HFT signal that I call "futures lead."

The term that I will use for the type of link among adjacent fields on which I will focus is taken not from field theory per se, but from Abbott's "linked ecologies" perspective: a "hinge," in other words, a process that generates rewards in more than one field or, in Abbott's terminology, more than one "ecology." (Although Abbott's perspective is not ordinarily thought of as a field theory, an ecology is a field-like "set of social relations . . . best understood in terms of interactions between multiple elements that . . . constrain or contest each other," just as the actors in a field do [Abbott 2005, p. 248].)[5] The attractively succinct term "hinge" aside, what makes Abbott's work on linked ecologies particularly relevant here is his discussion of how the temporal rhythm of one pervasively important ecology, politics, differs from that of many others. Issues that are continuously important in one or more of those other fields or ecologies (medical licensing in Abbott's main example of linked ecologies; here, how shares should be traded) are often only sporadically salient politically, because most of the time there are few political rewards for pursuing them.

The hinges that link politics to the fields or ecologies of trading, exchanges, and financial regulation—or, in Abbott's chief example, the ecology of the professions—are thus typically transient and contingent, even idiosyncratic. (Idiosyncrasy needs to be emphasized: the overall research found no common pattern to the hinges to politics in the different markets examined.) What follows, however, does not entirely confirm Abbott's assertion of "the near impossibility of creating institutionalized linkages between ecologies. . . . There is . . . no way to build a perfect hinge" (2005, pp. 247–48, 269). One signal to be discussed below—futures lead—does involve an institutionalized hinge between politics and the ecologies of finance.

The article proceeds as follows. A brief description of data sources ends this introduction. The second section draws on my interviews with high-frequency traders to identify the main classes of HFT signal and their roles in how algorithms interact. Then follows a section on how the first class of

[5] In an unpublished section of Abbott (2005), he points to differences between his approach and what he suggests are over-rigid aspects of Bourdieu's field theory (Abbott, n.d.; see also, e.g., Bourdieu 1984, 1996). It is far less clear, though, that there are any profound differences between Abbott's approach and the more flexible field theory of Fligstein and McAdam (2012). Furthermore, while Abbott's definition of ecology is not explicitly meso-level, nearly all his actual examples are. Unfortunately, however, neither Fligstein and MacAdam (2012) nor Kluttz and Fligstein (2016) consider Abbott's work in their discussions of field theory. For a previous application of Abbott's linked ecologies to financial regulation, see Du Gay, Millo, and Tuck (2012, pp. 1090–93).

signal—futures lead—came into being and two sections (Centralization versus the Intermarket Trading System and HFT and the Transformation of Share Trading) that examine two phases in the later, interwoven emergence of the second and third classes. The second of those sections also sketches the process by which algorithmic trading has come to dominate the U.S. stock market. A sixth section briefly compares the trading of shares to that of futures, Treasurys, and foreign exchange. The seventh section is the conclusion.

Data Sources

This article draws on interviews with 194 market participants, including 54 founders, employees, or ex-employees of HFT firms (see table 3). Because of commercial confidentiality, HFT's material practices are a tricky topic for interviewing, so a fixed interview schedule could not be employed.[6] The interviews with high-frequency traders were more like conversations, while I tried gently but persistently—and with widely varying degrees of success—to elicit information on HFT practices, the influences on those practices, and (if the interviewee had long enough experience of HFT) changes in those practices through time. Nor, given the absence of any list of high-frequency traders, could probabilistic sampling be used. I began by approaching traders identified via the trade press or, for example, whom I met at industry meetings and then snowballed from these initial interviewees. As differences between HFT practices in different markets emerged, interviewing was extended to members and staff of exchanges and other trading venues and to regulators involved in particularly crucial episodes, to help understand the different paths of change followed by different markets. The other categories of interviewees listed in table 3 provided either specific information or useful triangulation. For example, what HFT interviewees said about the signals employed by their algorithms was cross-checked by interviewing those who supply HFT firms with the communication links via which signals are transmitted.

I was also able to visit two of the data centers in which HFT takes place, attended two HFT industry meetings and an algorithmic trading training event, and was often shown round HFT firms' offices before or after interviews. In the historical aspects of the research, documentary sources—including the trade press and the memoirs of key participants, such as the Chicago Mercantile Exchange's Leo Melamed (Melamed and Tamarkin 1996)—were consulted wherever available. The emergent literature on HFT

[6] A report for the U.K. Government's Foresight Project on HFT (Brogaard 2011) was, however, helpful in framing my initial questions on algorithms' use of signals.

TABLE 3
Interviewees

Type	Number
High-frequency traders (AA–CC)	54
Exchange and trading venue members and staff (EA–GB)	54
Dealers, brokers, and broker-dealers (DA–DT)	20
Institutional investment firms' traders (IA–ID)	4
Practitioners of other forms of algorithmic trading (OA–OM)	13
Manual traders (MA–MH)	8
Regulators (RA–RH)	8
Suppliers of technology and telecommunications links to HFT (SA–SR)	18
Researchers/market analysts (UA–UO)	15
Total	194

Note.—In the text, interviewees are identified by two-letter labels, specific to each category, in chronological order by the date of the (first) interview with them.

in financial economics (most recently reviewed in Menkveld [2016]) was carefully read for the evidence that some of it contains on whether particular classes of signal do indeed have potential predictive value and whether trading patterns are consistent with use of those signals in HFT.

SIGNALS AND HOW THEY INFLUENCE HOW ALGORITHMS INTERACT

To understand how signals influence the behavior of HFT algorithms, we need first to describe the main way in which those algorithms materially interact with each other, with execution algorithms, and indeed with human traders: by entering orders into an exchange's "order book," an electronic file of the bids to buy each stock and the offers to sell it. (See fig. 3 for a visual representation of an order book.) In traders' terminology, a new order either "takes" or "makes." An order that "takes" is one that an exchange's "matching engine" (the software that maintains the order book) can execute against an existing order already in the book: in figure 3, a new order to buy shares at $7.75 would take because it would be executed against existing offers to sell at $7.75. In contrast, an order that "makes"—or, as traders would often put it, that "provides liquidity"—is one that cannot immediately be executed (in fig. 3, an example would be an order to buy shares at $7.74, a price at which there are no existing offers) and is therefore simply added to the order book.

While an algorithm can both take and make, interviewees consistently reported that they themselves, their algorithms, groups of traders, and sometimes even entire firms tend to specialize in one or the other. Taking is faster than making (a making order may indeed never be executed) but is also nor-

Bids to buy		Offers to sell	
		↑	
		$7.78	400
		$7.77	1091
		$7.76	800
		$7.75	488
192	$7.74		
500	$7.73		
1500	$7.72		
1300	$7.71		
	↓		

FIG. 3.—Order book for shares of Astoria Financial Corp. on Nasdaq, c. noon, October 21, 2011. On the left-hand side are the aggregated bids to buy Astoria shares: for example, there are bids to buy 192 shares at $7.74. On the right-hand side are the corresponding offers to sell. Source: extracted from figure 5.

mally at least a cent per share more expensive: in the example just given, taking involves buying shares at $7.75 or more, while a maker can hope to buy at $7.74 or less. (In share trading, most exchanges also now incentivize liquidity provision by making small payments—known as "rebates"—to firms whose making orders are executed against. Liquidity takers, in contrast, have to pay fees to the exchange.) The greater expense of taking means that an algorithm will do so only if it receives a relatively clear indication—a strong signal—that prices are about to move sufficiently to make that profitable.

A former high-frequency trader, in informal conversation, gave a simple example. If a liquidity-taking algorithm in one of the New Jersey data centers is trading shares in the SPY (a type of share—an "exchange-traded fund" or ETF—that tracks an index, in this case the Standard and Poor's [S&P] 500) and it learns that the market price of the ES or "e-Mini" (a futures contract that tracks the same index) has suddenly increased by "four ticks [price increments]," that is an unequivocally strong signal. The taking algorithm will immediately dispatch an electronic order to buy whatever SPY shares are still offered at the old price (a price that market participants would call "stale"). Many of those offers will have been entered by HFT algorithms that specialize in the systematic form of liquidity provision known as "market making," which involves constantly keeping in order books both bids to buy and slightly higher-priced offers to sell. These making algorithms will also receive the same signal from the futures market and will seek as quickly as possible to "get out of the way," as a specialist in making would say: to cancel their now stale offers and replace them with new offers at a higher price. As CB, a specialist in market making, put it, "our need for speed . . . is almost without exception defensive in nature," but it is no less pressing for that.

In the terminology of the field, taking algorithms thus often seek simply to "pick off" (to execute against) knowably stale bids or offers, while making algorithms—receiving the same signal—seek to cancel such bids or offers before they are executed against. It is a very simple pattern of interaction (more subtle patterns are discussed at the end of this section), and the economics literature on HFT contains a straightforward, insightful model of it (Budish, Cramton, and Shim 2015). It is, however, as Budish et al. point out, the core driver of a ceaseless "arms race" pursuit of speed, which takes material form both inside data centers and in the microwave, millimeter wave, and laser links among them.

But what are the material signals that indicate to both taking and making algorithms that a bid or offer is stale? As already noted, a "signal," as high-frequency traders use the term, is a pattern in the data received by an HFT algorithm that can be used to inform the algorithm's trading: typically, a pattern that has predictive value. It was, of course, not feasible for me simply to ask traders to list the signals their algorithms use: that would at best cause unease. Nevertheless, the HFT interviews—along with cross-checking with suppliers of communication links and with the economics literature on HFT—led to the identification of the seven classes of signal listed in table 1.

Futures Lead

The example given above of the ES share-index future ticking up four points is an instance of the signal that I call "futures lead" (there is no set "native" term for it). Futures lead was hugely important to the emergence of HFT in the 1990s, because at that point the second and third classes of today's HFT signals (order book dynamics and "fragmentation") did not yet exist, at least in full, usable form. The dominant venues for U.S. share trading were the New York Stock Exchange (the NYSE did disseminate the sizes and prices of transactions, but the contents of its order books were private to designated traders called "specialists") and Nasdaq, which did not have central order books. The NYSE and Nasdaq did not compete directly with each other, meaning that fragmentation was limited. The NYSE traded only NYSE-listed shares; Nasdaq traded only shares not listed on the NYSE or other exchanges.

In futures lead, any substantial change in the prices of, or order books for, share-index futures is treated by HFT algorithms as indicating a likely near-term change, in the same direction, in the market for the underlying shares. Interviewee EH emphasized the signal's importance to taking algorithms: if "the futures move up . . . shoot to a premium . . . then they'll [taking algorithms will] take all the underlying cash [buy the corresponding ETF and/or the shares underpinning the index tracked by the futures contract]." Futures lead is at least equally important for market-making algorithms. "If you're making a market in . . . SPY [the ETF share that tracks the S&P 500], certainly seeing something big happening in ES [the corresponding futures contract]" means that your algorithm needs immediately to "get . . . out of the way," says interviewee AX. "Sure, we [our algorithms] utilize futures prices for making predictions in U.S. cash equities [shares]," says market-maker BL. If "the S&P Mini [ES index future] in Chicago has exhausted at a certain level [all the bids or offers at that price have been executed against or canceled], we know with certainty that something is going to happen in the U.S. equity market. So we can't just be sitting out there waiting to get picked off," says CB.

Interview testimony such as this is backed by econometric evidence that (*a*) movements in the futures market do indeed have predictive value (see, e.g., Hasbrouck 2003) and (*b*) HFT firms trade U.S. shares in ways consistent with their use of this signal (see Brogaard, Hendershott, and Riordan 2014).[7] Further evidence of the salience of futures lead is the huge importance that HFT firms trading shares in the data centers in New Jersey place on the material means by which signals are transmitted from the Chicago futures markets. The best-known example (because it is described in Lewis's [2014] bestseller *Flash Boys*) is the laying of a new fiber-optic cable, which entered use in 2010, that closely follows the geodesics from Chicago to northern New Jersey (see fig. 4), and was therefore faster than any previous cable. As Lewis says, and former high-frequency trader Peter Kovac (2014, p. 1) confirms, the cable's owner, Spread Networks, charged HFT firms $176,000 a month to use the cable's fastest fibers and—interviewee BB reports—insisted that users sign a nonrevocable five-year contract. HFT firms making markets in U.S. shares and taking firms whose algorithms employed futures lead had, however, little choice but to accept these onerous terms.

The Chicago–New Jersey speed race, however, both predates the Spread cable and has continued since. Early in the 2000s, a telecommunications specialist approached a Chicago HFT firm with the proposal to help it find what Chicago traders came to call "the gold line." This involved identifying segments of existing fiber-optic cables that could, as interviewee CC told me, be "pars[ed]" or "knit[ted]" together to form the fastest route, and then persuading their owners to lease them: "No, I don't want to go through the

[7] The evidence of this in Brogaard et al.'s (2014) study is indirect, since they do not employ Chicago Mercantile Exchange data, but there is direct evidence of exploitable opportunities in the study by Budish et al. (2015), who do.

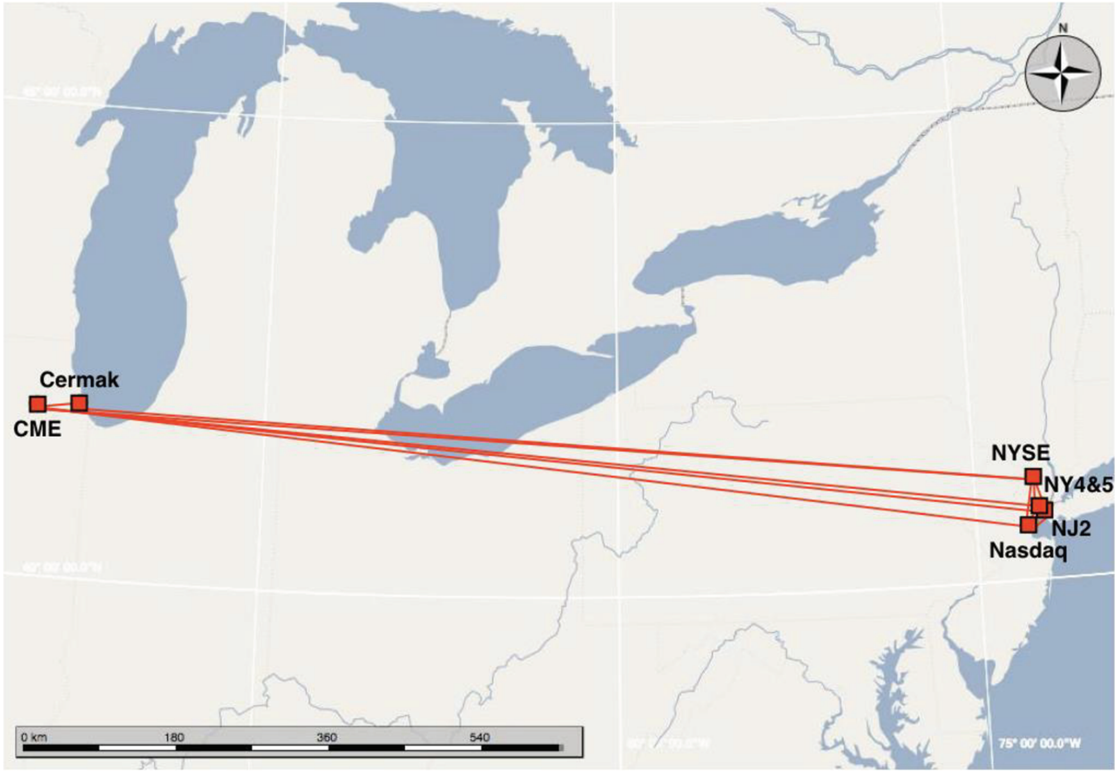


FIG. 4.—Geodesics from Chicago to the New Jersey share-trading data centers. CME is the main Chicago Mercantile Exchange data center in the city's western suburbs; Cermak, just outside the Chicago Loop, is a multiuser data center, hosting both share and futures trading. The CME's matching engines were in Cermak until 2010.

switching station in [town A]. I want to go to the switching station in [town B].” The exact route of the gold line is unclear (other interviewees who worked for the firm in question in that period either did not know the route or were reluctant to disclose it), but CC says—plausibly—that it roughly followed Interstate 80 across northern Ohio, Pennsylvania, and northern New Jersey. Having the gold line, interviewees reported, helped make the firm the prime proponent of HFT until around 2011.

Light in a fiber-optic cable is, however, slowed by the fiber's refractive index, which is around 1.5 (e.g., 1.47 for Lucent TrueWave RS, the material of the Spread cable). Fiber-optic signals therefore travel at only about two-thirds of the speed of light in a vacuum. The refractive index of the atmosphere, in contrast, is very close to 1.0. In consequence, since 2011 the unequivocally fastest form of transmission from Chicago to New Jersey has been microwave. (The millimeter wave and laser transmission used within New Jersey so far has been less attractive over the 1,200 kilometers from Chicago because many more intermediate towers and signal regenerators/amplifiers would be needed. To accommodate microwave's more limited bandwidth, only the most directly relevant futures data are transmitted.)

Although the Chicago–New Jersey microwave links are now within less than 50 microseconds of the Einsteinian limit, there is relentless pressure, described by interviewee SJ, to keep speeding them up. There is constant jostling to place microwave dishes on existing towers, or build new towers, as close as possible to the geodesic. Every unnecessary meter traveled is now shaved off, for example, by placing microwave amplifiers/repeaters high on the towers rather than having signals go down the tower to a bunker at its base and then back up again.

These ultrafast microwave links can, however, be interrupted by the most mundane of material phenomena—rain (and also snow)—which, as a result, can influence how HFT algorithms interact. Consequent effects on patterns of U.S. share prices have been documented in the financial economics literature (Shkilko and Sokolov 2016). When microwave links created by HFT firms first became fully operational in 2011–12, the fastest of those links were employed by taking algorithms to pick off market-making algorithms. When rain or snow led the links to fail, the speed advantage of these taking algorithms was removed, and standard measures of liquidity therefore improved. By the end of 2012, however, HFT firms more generally had begun to rent microwave bandwidth or to buy ultrafast data from a technology supplier, McKay Brothers, whose Chicago–New Jersey microwave link was, and is, at least as fast as the quickest privately owned links. Doing so reduced the risk of market-making algorithms being picked off, so these effects of rain on liquidity vanished again. (My interview data suggest they have been replaced by a different effect of rain on the interaction of HFT algorithms, but space constraints prevent discussion of it here.)

The materiality of futures lead had another intriguing aspect, first hinted at in an October 2011 interview:

> Interviewee AC: Some companies don't wait for the [Chicago Mercantile] Exchange to tell them what's trading.
>
> Author: Oh, so how do you manage to . . .?
>
> Interviewee AC: That I can't. . . . I mean not only would I lose my job, I might lose my legs too!

(In a later interview, AC said that he had received this warning from a senior member of his firm: "The look on his face was stone seriousness. He was not joking at all.") When the issue surfaced in the *Wall Street Journal* (Patterson, Strasburg, and Pleven 2013), AC confirmed what he had previously hinted at: when one of a trading firm's bids or offers had been executed, Globex (the Chicago Mercantile Exchange's electronic trading system) would often send the firm the electronic "confirm" message a fraction of a second before the transaction appeared in the general Globex data feed. A confirm could therefore provide a vital early indicator that the prices of futures were moving, thus giving a structural advantage to those share-trading HFT firms, often based in Chicago, that also traded share-index futures (interviewee EW). As Globex was reengineered, the time difference shrank; but even in 2013, reported interviewee AJ, "you know about your fill one to two milliseconds [thousandths of a second] ahead of everyone else." With HFT response times measured by then in millionths of seconds, that was potentially of great importance.

Order Book Dynamics

Historically primary though it was, and important as it still is, futures lead is often eclipsed as an everyday concern of high-frequency traders by a much wider, and more complex, second class of signal, order book dynamics: transactions in the shares being traded and other changes in the order book for them. One example of this class of signal is a changed balance of bids to offers. If, for instance, "there are more buyers than sellers . . . that signal . . . we try to detect before anyone else" (interviewee AM). A situation of that kind—in which bids clearly outweigh offers—would be described by my interviewees as a situation of "order book pressure," signaling a coming price rise (or a fall, if offers greatly exceeded bids). The predictive value of the signal, and a pattern of trading consistent with its use by HFT algorithms, is confirmed by the economics literature (Brogaard et al. 2014). The necessary level of sophistication in how HFT algorithms process order book data has, however, increased through time. In the early 2000s, said AG, "you could basically say 'is the bid bigger than the offer?' and . . . not to say that that's completely meaningless today, but it would be a lot more nuanced than that."

Today's stock exchanges do not directly disseminate the electronic equivalents of figure 3: that would be too slow, because the complete order book for a heavily traded stock is a large data structure. Rather, following the practice of the 1990s share-trading venue Island (discussed below), each update to the order book—each transaction, each new order, each cancellation of an existing order—is disseminated by an exchange's "feed server" or "market data publisher" system as a separate message; the vast flow of messages among data centers referred to in this article's initial paragraphs consists mainly of these updates. Trading firms' computer servers use these messages to synthesize a continuous "mirror" of the exchange's order book.[8]

It is hugely important to HFT firms that their algorithms receive this stream of order book update messages as quickly as possible. That is one of the two main reasons for HFT's most distinctive spatial aspect: "colocation," which involves placing HFT firms' servers in the same building as, and within that building as close as possible to, an exchange's "matching engines," which, as noted, are the computer systems that maintain order books. (The other main reason for colocation is so that the matching engines receive HFT algorithms' bids, offers, and cancellations with the minimum delay.) Interviewees reported that, in most trading of U.S. shares and futures, cables are coiled so that the length of the connection of each trading firm's servers to the order gateways—the portals to the matching engines—is the same. However, a structural advantage can be gained by paying higher fees (of around $20,000 monthly) for a connection that has a higher bandwidth (and is therefore normally faster, even with equal cable lengths) or fewer digital switches between the firm's servers and the matching engines. Interviewee SJ's firm, for example, has measured an average time difference of three microseconds (three times interviewee AG's one-microsecond HFT benchmark) on one exchange between the standard and the fastest connection.

Fragmentation

"Fragmentation" is what I call the third class of signals: again, there is no settled participants' term. It arises because the same shares are traded on more than one exchange or trading venue. (There are 13 registered exchanges on which U.S. shares are traded, the computer systems of all but one of which are in data centers illustrated in fig. 1, and also around 40 trading venues that are not exchanges, of which most are "dark pools," in which the order book is

[8] Most exchanges allow trading firms to submit "hidden orders," which are not disseminated; those orders, however, are placed behind visible orders in the queue for execution.

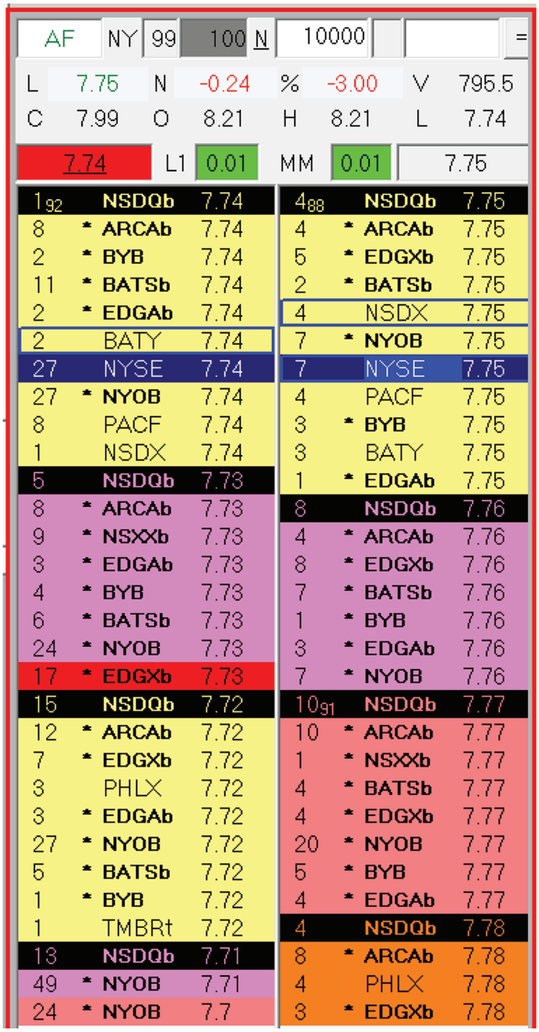
not visible.) The simplest form taken by fragmentation is the case in which shares can be bought on one trading venue more cheaply than they can be sold on another. That, however, is increasingly rare, interviewees reported: "it happens less frequently and [it is] not a key part of the [HFT] business" (AX).

The much more pervasive use of fragmentation is the case in which the buy, sell, and cancellation decisions by an algorithm trading shares on one venue are informed by signals in the data feeds from other venues that indicate significant transactions or other changes in their order books for the same shares. A standard HFT practice is for a firm's servers locally to aggregate all these separate order books: "I just wrote that code last week," interviewee BQ told me (see fig. 5 for a visual representation of a composite order book of this kind). "Maybe on top of the composite [order book] you also say, I know this exchange is the fastest so I give a little bit more juice [a heavier weighting in the algorithm's calculations] to the orders from that exchange," said BV.

The continuous updating of composite order books by HFT firms' servers creates tight, ultrarapid linkages among the five main share-trading data centers: if, for example, a large buy order is executed in one data center, "other participants are going to be pulling that stock [their algorithms will be canceling their offers] from those [other] venues," said BL. "You're looking at the . . . order books for all the different markets," he continued: "every little change to those [data] feeds [from those markets] is digested and calculated locally in numerous different geographic locations, and you're passing all that data in real time between locations. . . . That's where your investment in low-latency technology really is."

The huge volumes of data that therefore need to be transmitted among the five share-trading data centers mean that microwave links are not employed. Their bandwidth is insufficient, and the difficulty of gaining permission to build tall enough towers in prosperous areas of New Jersey—especially, as interviewee SJ told me, at or close to the NYSE data center, which is in a dip in the terrain—removes the speed advantage that they would otherwise have over higher-bandwidth millimeter wave and atmospheric laser links. (Microwave is potentially faster because it has no need for intermediate amplification at the distances involved in New Jersey; but microwave signals require a direct "line-of-sight" path, and so tall towers are needed if source and receiver are far apart.) Again, spatial location can yield structural advantage. In the case of millimeter wave, for example, firms want to place their dishes directly on the roofs of the five data centers rather than on towers outside them.[9] They can pay to do this on the roofs of NY4, NY5, and NJ2, but Nasdaq and the NYSE themselves supply millimeter

[9] The point is to minimize what those involved call "fiber tail": the distance over which a signal has to run through fiber-optic cable, with its higher refractive index.



AF	NY	99	100 N	10000	=
L 7.75	N -0.24	% -3.00	V 795.5		
C 7.99	O 8.21	H 8.21	L 7.74		
7.74	L1 0.01	MM 0.01	7.75		

1$_{92}$	NSDQb	7.74	4$_{88}$	NSDQb	7.75
8	* ARCAb	7.74	4	* ARCAb	7.75
2	* BYB	7.74	5	* EDGXb	7.75
11	* BATSb	7.74	2	* BATSb	7.75
2	* EDGAb	7.74	4	NSDX	7.75
2	BATY	7.74	7	* NYOB	7.75
27	NYSE	7.74	7	NYSE	7.75
27	* NYOB	7.74	4	PACF	7.75
8	PACF	7.74	3	* BYB	7.75
1	NSDX	7.74	3	BATY	7.75
5	NSDQb	7.73	1	* EDGAb	7.75
8	* ARCAb	7.73	8	NSDQb	7.76
9	* NSXXb	7.73	4	* ARCAb	7.76
3	* EDGAb	7.73	8	* EDGXb	7.76
4	* BYB	7.73	7	* BATSb	7.76
6	* BATSb	7.73	1	* BYB	7.76
24	* NYOB	7.73	3	* EDGAb	7.76
17	* EDGXb	7.73	7	* NYOB	7.76
15	NSDQb	7.72	10$_{91}$	NSDQb	7.77
12	* ARCAb	7.72	10	* ARCAb	7.77
7	* EDGXb	7.72	1	* NSXXb	7.77
3	PHLX	7.72	4	* BATSb	7.77
3	* EDGAb	7.72	4	* EDGXb	7.77
27	* NYOB	7.72	20	* NYOB	7.77
5	* BATSb	7.72	5	* BYB	7.77
1	* BYB	7.72	4	* EDGAb	7.77
1	TMBRt	7.72	4	NSDQb	7.78
13	NSDQb	7.71	8	* ARCAb	7.78
49	* NYOB	7.71	4	PHLX	7.78
24	* NYOB	7.7	3	* EDGXb	7.78

FIG. 5.—Orders for shares of Astoria Financial Corp. on U.S. trading venues, c. noon, October 21, 2011. Note that the zeroes of "round-lot" bids and offers are not displayed (a round-lot order is for 100 shares or an integer multiple of 100). Thus the first three bids in the left-hand column are for 192, 800, and 200 shares. Source: interviewee.

wave links (via contractors) and—citing space limitations and risks of radio interference—have gained the SEC's permission to restrict other firms' access to their roofs or, in the case of NYSE, to a pole that has been erected within the grounds of its data center (SEC 2013, 2015).

Other Shared Signals

The correlation between the prices of the same shares traded on different exchanges is of course very high, but there is also a fourth, wider class of signals in extensive use in HFT, in which correlation levels are lower but still useful: for example, movements in commodity prices or currencies that correlate with share prices, or changes in the prices of shares in corporations that are viewed as being in the same sector. "Citibank moves, what does that mean for Bank of America?" (interviewee BL). "There are correlations that are not structural in nature . . . for example the relationship between Microsoft and Oracle," said interviewee AE. "They are companies that are in the same industry, so they'll be correlated because they're driven by common factors like demand for certain kinds of software or economic growth more generally, or the fact that, you know, people's hedging patterns [make] them correlate or the fact that they're in the same index, or what have you."[10]

The four classes of signal just discussed are "about 99% of everything" in HFT in shares, interviewee BL told me, and—despite extensive probing—I have not found another class that is anything like as widely used (see table 1). For example, while some HFT firms do make use of machine-readable corporate or macroeconomic news, that is a specialized activity: on the microsecond timescale of HFT, items of news of this kind (or, e.g., changes in social-media "sentiment") are very rare events. There is of course secret sauce, but from interviewees' generic descriptions of its contents, it seems mainly to concern how best to employ the four main classes of shared signal, especially the most complex of them, order book dynamics.

More Subtle Forms of the Interaction of Algorithms

The interviews also suggest, however, forms of algorithmic interaction different in kind from the simple speed-race interaction of making and taking algorithms discussed above. One such form is the interaction between HFT algorithms and "execution algorithms," which, as noted in the introduction, divide up large orders from institutional investors into small, hopefully inconspicuous, child orders. That was a particularly difficult topic to explore in interviews: HFT interviewees are sharply aware of accusations (see, e.g., Lewis 2014) that HFT algorithms identify and prey on execution algorithms, for example, buying shares ahead of them and then selling those shares to them at higher prices. Some denied that their particular firm's al-

[10] Correlation or co-integration of this sort is widely documented in the economics literature, albeit generally at timescales quite different from those of HFT (e.g., the daily data used by Gatev, Goetzmann, and Rouwenhorst [2006]). For pointers to a sociological analysis of it, see n. 4 above.

gorithms did this while acknowledging it was possible to do it; others simply said that a big institutional order inevitably had detectable effects on order book dynamics, despite efforts to disguise those effects by randomizing the sizes and arrival times of child orders. Execution algorithms are still "extremely predicable," said HFT interviewee AO: "I don't really think they have any other way of being." Execution algorithms "can't randomize that much," he went on, because of the constraint of having to execute the big parent order in a limited amount of time.

A different form of predictable behavior is that of HFT algorithms themselves. It arises from their pervasive use of the four main classes of signal (which, interviewees reported, are most usually combined in what is in effect simply a linear regression equation, the dependent variable in which is the predicted near-future price of the shares being traded). The simplest way of exploiting the resultant deterministic behavior is what participants call "spoofing," which involves manipulation of the material signal that is easiest to alter: the contents of the order book. A "spoofer" (human or algorithmic) injects orders into the book to create apparent "book pressure" (an excess of bids over offers, or vice versa) and profits from HFT algorithms' predictable responses to that pressure, while canceling the spoof orders before they are executed.

Although informally tolerated until quite recently (Arnoldi 2016), spoofing is now increasingly the subject of criminal charges that carry jail terms. There are, however, legal ways—generally involving taking liquidity rather than the (apparent) making liquidity involved in spoofing—in which more sophisticated algorithms can exploit deterministic behavior by simpler HFT algorithms. Nearly all today's electronic order books are anonymous, but some order book behavior has been in effect de-anonymized by technological advances in the system sketched at the start of this article: in particular, reduction in "jitter" (random speed fluctuations) in the processing of orders by exchanges and ultraprecise atomic-clock synchronization of time measurement across exchanges. These advances make it possible (although technologically still hugely challenging, because the data sets that need to be captured and analyzed are gigantic) to identify patterns in the order book's responses to specific material signals, patterns that are most likely the result of signal-determined actions by the same HFT algorithm and therefore likely to recur. The formal anonymity of today's order book trading can thus in effect collapse in the face of machine-learning technology that provides automated answers to questions such as "How much does this [order book event] look like previous events? How many of those previous events have I seen? So what is the probability that this is like all those previous events?" (interviewee AJ). None of this sophistication, however, reduces the importance of the main classes of signal as determinants of the behavior of HFT algorithms: indeed, what I have just described is in essence simply a different, more subtle analysis of order book dynamics. Furthermore, sophisticated prediction of this kind is, as it were, layered on top of "first-level," direct, algorithmic responses to the main classes of shared signals, which create the predictability that more sophisticated algorithms can sometimes exploit.

THE ORIGINS AND LONGEVITY OF FUTURES LEAD

What gave rise to these pervasively important shared signals in the first place? Let us begin with "futures lead." It is the result of an initially idiosyncratic early-1970s hinge between the fields of exchanges and of politics that has become institutionalized. The exchanges in question were futures exchanges, especially the Chicago Mercantile Exchange (CME), whose chair, Leo Melamed, was seeking greater legitimacy for a scandal-damaged sector and hoping to remove a legal obstacle to its expanding from agricultural commodities into financial derivatives, especially share-index futures (Melamed, interviewed by author, November 8, 2000). The obstacle was that Anglo-American law traditionally made the intention physically to deliver the underlying asset the distinction between a legitimate forward trade and a wager. If delivery was not possible and a contract could therefore be settled only by a cash payment, then it was a wager (and so illegal in Illinois, as in much of the United States). Since it would be at best clumsy to settle a share-index futures trade by the delivery of share certificates for dozens or hundreds of corporations, index futures could not be traded.

On the political side of the hinge, Texas Democrat Bob Poage, who chaired the House Agriculture Committee, was concerned by hostile hearings being held on agricultural futures by the chair of the House Subcommittee on General Small Business Problems, Iowa Democrat Neal Smith. As Melamed put it in his memoirs, Poage's committee (along with the Senate Agriculture Committee) "by tradition should have had jurisdiction over our markets. [Poage] knew nothing about futures and couldn't care less, but we [the Chicago exchanges] gained his ear, if for no other reason than to stop Smith from poaching on his jurisdiction" (Melamed and Tamarkin 1996, p. 215).

Melamed, Poage, and even Smith (see Smith 1996, pp. 262–64) found common ground in a proposal to create a new federal futures regulator to replace the existing small regulatory subunit of the Department of Agriculture. That would "legitimatize what we [the futures markets] were doing. Anyone that has a federal agency over it is a legitimate thing," says Melamed. Furthermore, because the gambling bans in the United States were state, not federal, law, a federal futures regulator could preempt them and "give [an] edict [legalizing] cash settlement" (Melamed interview). Working with the staff of the House and Senate Agriculture Committees, Melamed and his allies, notably Philip McBride Johnson, general counsel to the Chicago Board of Trade, helped draft appropriate amendments to the Commodity Exchange Act.

Their plans were nearly derailed when the Ford administration, which did not welcome the creation of an additional regulator, offered jurisdiction over the futures markets to the stock market regulator, the SEC: "We [the SEC] were asked whether we wanted that jurisdiction, and I have a pretty clear memory of some of the commissioners saying, 'what do we know about pork bellies!'. . . They have since come to regret that, but . . . I don't think there was any debate about it really. They all concluded they didn't want to deal with that" (interviewee RG). Pork bellies—huge slabs of frozen pork—seem to have epitomized the gross physicality of the assets underlying agricultural futures. Interviewee RF, also an SEC official in the 1970s, had the same recollection of the SEC commissioners' reaction: "Why would we mess around with pork bellies?" The way they reacted, he said, was "very snooty, very East Coast."

The SEC's rejection of jurisdiction had consequences that it simply failed to foresee. In drafting the amendments to the Commodity Exchange Act, Melamed's ally Johnson had added 20 carefully chosen words to the long list of commodities ("wheat, cotton, . . .") whose futures trading was governed by the act: "and all services, rights, and interests in which contracts for future delivery are presently or in the future dealt in" (Falloon 1998, p. 247; Committee on Agriculture and Forestry, U.S. Senate 1974, p. 27). The resultant change in the law was, in Abbott's (2005, p. 248) terminology, "ligation." Rather than simply reallocating jurisdiction over existing regulatory tasks, the creation of the new regulator, the Commodity Futures Trading Commission (CFTC), was simultaneously the creation of new tasks: new markets, previously illegal, that the CFTC would regulate and thereby make legally permissible. Without mentioning futures on share indexes explicitly—that overt intrusion into its jurisdiction would immediately have sparked SEC opposition—Johnson's words implicitly cleared the way for them.

Under its Carter-appointed chair, James Stone, the CFTC did not immediately give Melamed's desired "edict" ending the requirement for physical delivery. In 1981, however, Reagan appointed Melamed's ally Johnson CFTC chair, and it then did so. A fierce jurisdictional dispute between the CFTC and SEC finally broke out over index futures, but Johnson's careful drafting had weakened the SEC's legal position, and a deal struck between him and John Shad, Reagan's appointee as SEC chair (Millo 2007), permitted the CME to launch S&P 500 futures in April 1982.

The new share-index futures, regulated by the CFTC, not the SEC, followed the procedures of futures trading, not those of share trading, which gave them structural advantages over the latter. It was simpler, faster, and cheaper to trade a single future than to buy or sell the 500 stocks underpinning the

S&P index, and creating a "short" position—one that would benefit from price falls—was a matter merely of selling the future. "Shorting" shares, in contrast, was cumbersome (it required one to borrow shares, sell them, and then buy them and return them) and was hemmed in by regulation: shorts were often blamed for share price falls. Furthermore, as with other futures contracts, one could trade S&P 500 futures with only a modest "margin" deposit with one's broker or the CME's clearinghouse, a deposit that one had to add to only if prices moved against one. The regulations governing share trading, in contrast, made it very difficult to achieve an equivalent level of "leverage": the size of a trading position relative to the required level of capital.

Simplicity, cheapness, ease of shorting, and high leverage made the new S&P 500 futures an attractive way of profiting quickly from (or hedging against the arrival of) new information relevant to the overall value of U.S. shares. As a result, it soon became clear that despite the fact that the CME had no previous involvement with shares, the prices of its S&P 500 futures tended to move before—in 1984–85, as much as 20–45 minutes before—the prices of the underlying shares (Kawaller, Koch, and Koch 1987, p. 1309). Futures lead had come into being, and—although it has now shrunk to less than a hundredth of a second (see, e.g., Budish et al. 2015)—it still largely persists, remaining a vitally important signal in HFT in U.S. shares, with, as described above, huge investment in the material means of transmission from Chicago to New Jersey.

It is particularly noteworthy that, at least until very recently (interviewees BQ and BV report a gradual shift toward bidirectional influence), futures consistently led even the corresponding ETFs, which are shares that are often close to economically identical to futures. The most widely traded of all the ETFs—indeed, the world's most widely traded share—is the already-mentioned SPY, an ETF set up in 1993 that tracks (albeit by a different mechanism) the same index as the ES, the CME's S&P 500 future. The two instruments differ economically in only minor ways, yet for more than two decades the future (the ES) still consistently led the share (the SPY), as is confirmed by both interviewees and econometric evidence (Laughlin, Aguirre, and Grundfest 2014; Budish et al. 2015; Shkilko and Sokolov 2016).

Why? Why does futures lead, with its idiosyncratic origins in the 1970s and 1980s, largely persist in today's world, in which many shares are now sophisticated, algorithmically constructed ETFs, and in which—as we shall see below—there are other important classes of financial instrument in which futures do not lead the underlying asset? There are two main explanations, not mutually exclusive. The first is that liquidity is path dependent. If an institutional investor wants to execute a very large trade (e.g., the sale of 75,000 ES contracts, the equivalent of selling shares worth $4.1 billion, which triggered the May 2010 "flash crash" in U.S. share prices; see CFTC/

SEC 2010), she or he will turn to the market best able to handle the largest trades, which is still, participants report, the CME's index futures. In so doing, she or he helps keep that market able to do so and thus helps its prices to continue to lead those in other markets. The very belief that futures lead the underlying shares (a belief held by humans, but also, as we saw in the previous section, programmed into algorithms) further sustains that pattern, as those algorithms immediately raise share prices when futures prices rise markedly.

The second explanation of the entrenched nature of futures lead is leverage. While ETFs such as the SPY have many of futures' original advantages—for example, it is reasonably straightforward to use an ETF to establish a short position—it is still easier to achieve high leverage in futures than in shares (including ETFs). "Futures is first, right, because of the leverage it provides. . . . You're going to hit the [ES] first," said interviewee AP. Leverage is built into the very design of futures contracts, while if you are a small or medium-sized firm trading shares, a former high-frequency trader told me in conversation, achieving high leverage requires you to find a broker-dealer prepared to grant it to you.

This continuing difference between how futures and shares are traded (even ETF shares, which as noted can be close to economically identical to share-index futures) has rested at least to some degree on the continuing split in jurisdiction between the CFTC and SEC. From the 1987 stock market crash (which sparked influential demands to end the split and to harmonize leverage requirements) to the 2012 Frank-Capuano Bill, which proposed a merger of the CFTC and SEC, all efforts to create a single regulator have failed. The futures industry has fought, and would most likely again fight, such a move vigorously: the CME, now the world's leading exchange by market value—and one of the most profitable companies in the United States, with a ratio of operating profit to revenue of 64% (Stafford 2017)—has continued Melamed's emphasis on having a strong voice in Washington (Melamed and Tamarkin 1996; Meyer 2015; Stafford 2017). Such a fight has, however, mostly been unnecessary, because those who favor a CFTC-SEC merger are often dissuaded by an immediate barrier, which is in effect the institutionalization of the originally idiosyncratic 1970s hinge. The divide in the ecologies of finance (between futures trading and share trading; between futures exchanges such as the CME and stock exchanges; between the CFTC and SEC) is echoed in a divide between congressional committees, especially Senate committees. Because of futures' agricultural roots, the CFTC reports to the Senate Agriculture Committee, the SEC to the Senate Banking Committee.

"I've been in many conversations about the merger of the SEC and CFTC," former regulator RF told me. "The conversation quickly stops because people say, 'but the [Senate] Ag[riculture] Committee: this [merger] is never going to happen.'" Asked why the SEC and CFTC had never merged, another former regulator agreed: "You can probably begin and end your discussion with the Ag Committee. . . . It's powerful" (interviewee RG). If the SEC and CFTC merged, the Agriculture Committee would lose its jurisdiction over the latter and the regulation of financial futures: "that would then move [to] the jurisdiction of the Senate Banking Committee," to which, as just noted, the SEC reports (interviewee RF). Both interviewees cited the importance of campaign contributions from the finance sector (see fig. 6): "The Senate Ag Committee gets all of this money [contributions]. They're not going to give up jurisdiction, so you can't put it [the regulation of U.S. financial markets, currently split between the CFTC and SEC] together" (interviewee RF).

CENTRALIZATION VERSUS THE INTERMARKET TRADING SYSTEM

Just as the process that was to create futures lead was beginning in the mid-1970s, a separate struggle was taking place over how U.S. shares should be traded. That conflict shaped the overall configuration of the technological system in which today's share trading takes place, in particular, the crucial fact that trading is fragmented among different exchanges in the five data centers rather than concentrated in a single exchange in a single data center (as is the case, e.g., for the trading of financial futures). The struggle was again sparked by a hinge, here between the fields of politics and of regulation, but one that did not become institutionalized. As a result, the existing exchanges avoided a proposed centralization of share trading. Instead, they—especially the NYSE—created an electronically mediated but decentralized network, the Intermarket Trading System, which left existing trading floor practices largely intact. Simultaneously, however, the rejection of centralization created crucial latent preconditions for the second and especially the third class of HFT signals, fragmentation.

The trigger of the struggle over centralization was the 1960s boom in U.S. share trading. As volumes rose sharply, the manual processes that underpinned trading—the transfer of money and especially of shares (which were then still paper certificates)—became clogged. Piles of unprocessed documents, delays, omissions, errors (and even theft of share certificates) accumulated; emergency efforts at computerization were often failures; the "net effect of all of this was to turn the books and records of many broker-dealers into a veritable shambles" (SEC 1971*b*, p. 19). As the boom turned to bust at the end of the 1960s, stockbrokers began to fail in increasing numbers, threatening to leave hundreds of thousands of clients with large losses: for example, McDonnell & Company, which collapsed in March 1970, had had nearly 100,000 members of the public among its customers (Welles 1975, p. 172).

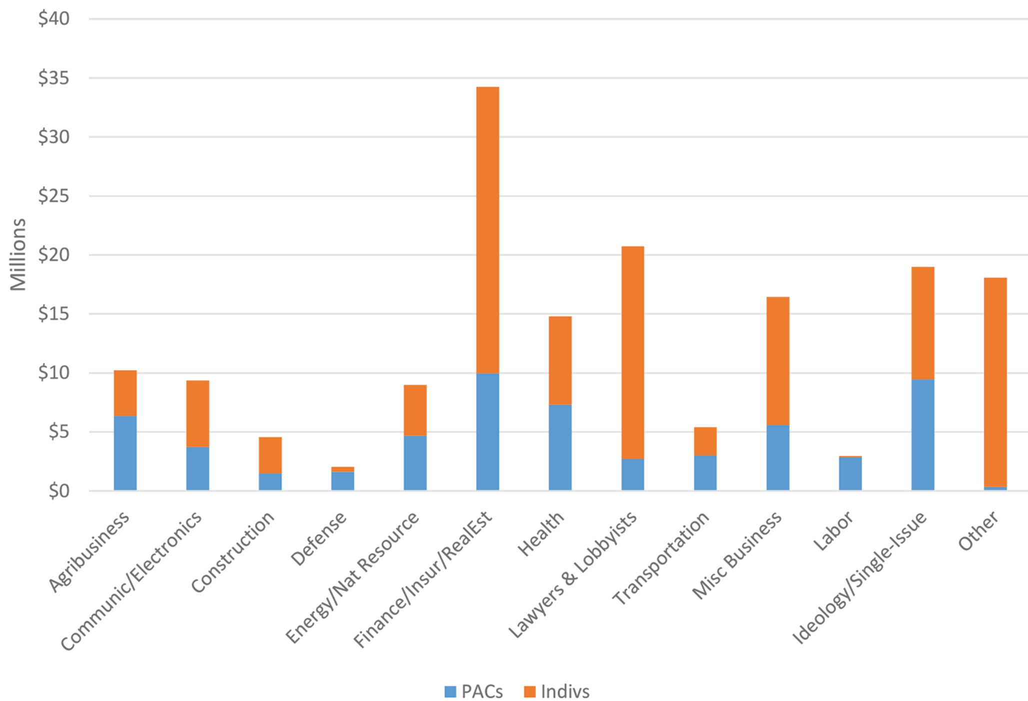


FIG. 6.—Sectors contributing to members of the Senate Agriculture, Nutrition, and Forestry Committee, 2016 election cycle. Data from http://www.opensecrets.org, accessed March 1, 2017.

The debacle created a situation (unusual, as noted in the introduction) in which there were potential political rewards from reforming how shares were traded. Led by Ed Muskie (who "was looking for big issues" on which to build his run for the 1972 Democratic presidential nomination; Lemov 2011, p. 120), Congress rapidly passed the 1970 Securities Investor Protection Act, which set up an insurance scheme, funded in part by the federal government, to compensate the customers of failed brokerages. The act did not, however, immediately exhaust congressional appetite for reform, although its leadership passed to less prominent figures: New Jersey Democrat Harrison Williams, who chaired the Securities Subcommittee of the Senate Banking Committee, and especially California Representative John Moss, the Democrat who chaired the House Subcommittee on Commerce and Finance and was building a reputation as a consumer protection advocate. As interviewees RE and RG reported, Williams and Moss each had aides who had been SEC officials. Moss's aide, former SEC staff attorney Harvey Rowen, led—with SEC input (interviewee RG)—the drafting of the resultant legislation, the Securities Acts Amendments of 1975 (Rowen, n.d.).

This SEC-congressional collaboration formed a hinge between regulation and politics. The 1975 amendments yoked together Congress's temporary enthusiasm for reform and long-standing SEC concerns about the extent of the structural advantages enjoyed by some traders and some exchanges (especially the NYSE), concerns expressed in two huge multivolume investigations, the *Special Study* (SEC 1963) and *Institutional Investor Study* (SEC 1971*a*), on the latter of which Moss's aide Rowen had worked. The SEC had, nevertheless, done little to act on these concerns: the statute that established it, the Securities Exchange Act of 1934, did not grant it unequivocal legal powers to impose a major structural change in how shares were traded. The 1975 amendments, however, gave the SEC clear authority, "by rule or order, as it deems necessary in the public interest and for the protection of investors . . . to remove impediments to and foster the development of a national market system and national system for the clearance and settlement of securities transactions" (Securities Acts Amendments 1975, p. 139).

Law, though, "has life only to the degree that those in power are willing to enliven it" (Danner 2017, p. 4). The political rewards for intervening in how shares were traded diminished as memories of the late 1960s crisis faded—Moss, for example, returned to more general consumer protection matters (Lemov 2011)—weakening the hinge. The SEC was left in the second half of the 1970s facing, largely on its own, an issue on which it had received no clear congressional guidance: the material design of the national market system that Congress had mandated it to create.

One proposed design was to remove barriers to competition and cut costs by creating a single, centralized, nationwide, electronic order book into which all orders to buy or sell shares had to be entered: the CLOB (consolidated limit order book), as it came to be called (Kennedy 2017). The CLOB's most prominent proponents were Junius Peake, who in the 1960s had led an early Wall Street computerization drive at broker-dealer Shields & Company, and Donald Weeden, whose family firm, Weeden & Company, was prominent in the "third market," a controversial penumbra of brokerages that—often in the face of fierce hostility from the NYSE—traded NYSE shares without going through the Exchange, undercutting the NYSE's fixed commissions (Weeden 2002). Mainstream if not entirely consistent support came from the nationwide brokerage Merrill Lynch, where (reported interviewee RH) another former SEC official had a senior advisory role.

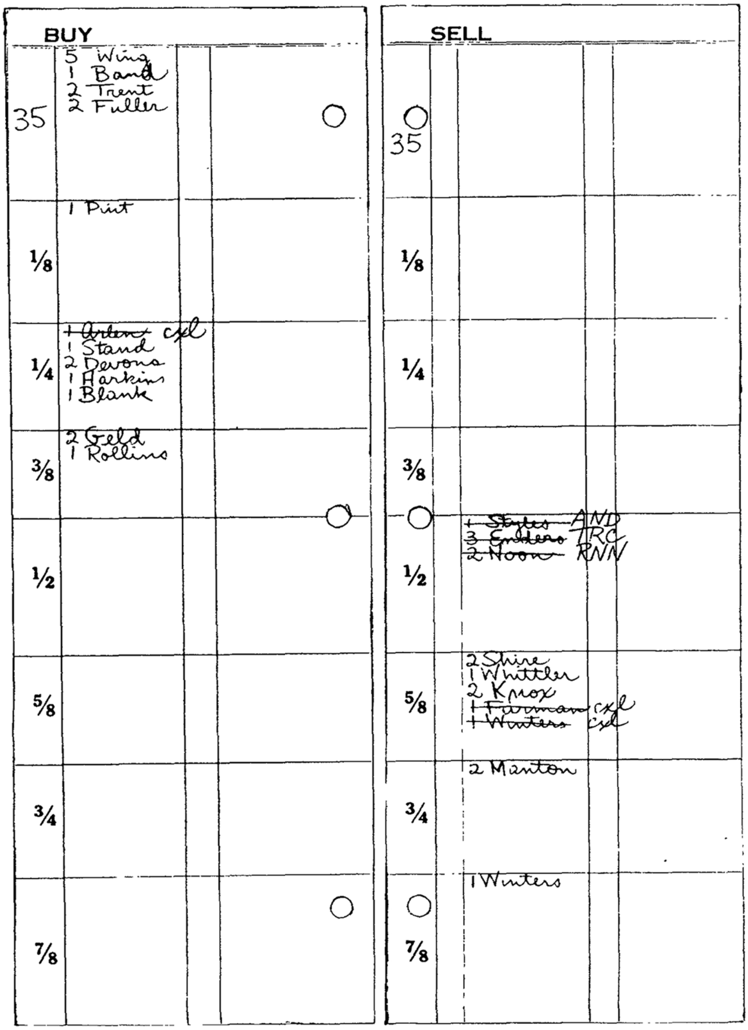
In the end, though, the SEC hesitated to back the CLOB. It would have ended the NYSE's system of specialists. Each stock traded on the NYSE had a designated trader who maintained the order book for it and executed trading floor or external customers' bids and offers that matched. These specialists, however, were also allowed to trade on their own behalf; indeed, they were obligated to do so if that were necessary to keep a stock trading continuously (see Abolafia 1996). The SEC was split internally, reports interviewee RF, on the wisdom of introducing a technological system that would eliminate specialists. Some SEC staff took "the view that [specialists] were basically rent takers" who exploited their structurally advantageous position, while others did not want to endanger "the benefits that [specialists] did provide" (interviewees RF and RE). There were, in addition, still hopes in the SEC that the existing regional exchanges in cities such as Philadelphia, Boston, and San Francisco might prove effective rivals to the NYSE, and a CLOB would end competition of that kind. The CLOB, furthermore, would have been an ambitious technological project, and President Carter's appointee as SEC chair, Harold Williams, was—as interviewees told me—ultracautious. In September 1979 testimony before the House Oversight and Finance Subcommittees, Williams told them, "I am not about to be the person to come back to Congress and say I am sorry I implemented your program and it blew [up]" (Subcommittee on Oversight and Investigations 1980, p. 2).

Three successive finance-sector committees were set up to advise the SEC, but their members included both proponents and opponents of the CLOB, and they therefore could not reach a clear recommendation. When I told interviewee RE that I had been unable to find in the NYSE archives the minutes of the apparently most important of these committees, the National Market Advisory Board, he told me that this did not matter: "They [the board] were going to argue about a question that had already been decided." Even if a CLOB was the best design for the national market system, and (as just noted) there were doubts in the SEC about that, "it was clear to us on the [SEC] staff that [the CLOB] just wasn't going to happen in the political realm that we were in." A proposal for a centralized national market system that threatened the very existence of the NYSE ("a very powerful institution back then," according to interviewee RE) and of regional exchanges that still had political clout was never going to succeed.

The NYSE itself took the lead in developing the alternative design of the national market system that was adopted in place of the CLOB: the Intermarket Trading System or ITS. It was based on an existing NYSE system (the Common Message Switch, which connected brokers' offices to the specialists' trading room booths) and thus could quickly be put into operation (Juan Pablo Pardo-Guerra, personal communication). The ITS's chief advantage, however, was that it was a compromise solution acceptable to all except the CLOB's strongest supporters. It operated in conjunction with the Consolidated Quotation System, which disseminated the best (i.e., highest-priced) bids and best (i.e., lowest-priced) offers on all the exchanges. If a specialist on, for example, the Boston Stock Exchange (such as interviewee MG) was given an order to buy, for instance, "telephone" (AT&T shares), he was supposed to fulfill it himself, whether on his own account or from his order book, only if there was no lower offer on another exchange. (Nearly all specialists were men; hence the masculine pronoun.) To sell shares on the floor of the Boston Stock Exchange at a price higher than, for example, the best offer on the NYSE would be a prohibited "trade-through," and if the NYSE specialist detected it, he could demand compensation. Instead, the Boston specialist was supposed to send a "commitment to trade" message, via the ITS, to the relevant specialist on the exchange with the cheaper offer, to which the latter had two minutes (eventually reduced to 30 seconds) to respond.

The ITS, launched in 1978, thus operated at a human pace and was often frustrating to use. If, for example, a specialist received a commitment to trade message seeking to execute against one of his quotes, he could simply decline to honor the quote, saying if challenged that he was in the process of changing it (interviewee RG). It thus remained simpler and quicker for most institutional investors to send large orders directly to the exchange with the most liquidity, the NYSE, rather than to use regional exchanges and the ITS. The latter nevertheless offered members of the regional exchanges something they craved: direct access to the NYSE trading floor and the capacity—especially toward the end of a trading day in which they had accumulated a position that they wished to unwind (interviewee MG)—to strike deals with specialists on the NYSE without having to pay a commission to an NYSE broker. The leaders of the regional exchanges therefore backed the ITS, despite pleas from CLOB advocate Donald Weeden for them not to do so (Weeden 2002, p. 106).

For the reasons just sketched, the ITS, in place from 1978 to the early 2000s, helped preserve the central role in U.S. share trading of the NYSE's trading rooms. Unlike the CLOB's proposed order book, which would most likely have been visible to all participants, the NYSE's order books (until the 1980s, handwritten on preprinted forms—see fig. 7—and then electronic) remained private to the "specialist" for the stock in question. In practice, a trading floor broker could perhaps glance at the book when a specialist or his clerk was entering his order (SEC 1963, pt. 2, p. 77) or, in later years,



	BUY	SELL
35	5 Wing 1 Band 2 Trent 2 Fuller	
⅛	1 Pint	
¼	~~1 Arden~~ cxl 1 Stand 2 Devons 1 Harkins 1 Blank	
⅜	2 Geld 1 Rollins	
½		~~1 Styles~~ AND ~~3 Gidders~~ TRC ~~2 Noon~~ RNN
⅝		2 Shire 1 Whittler 2 Knox ~~1 Farman~~ cxl ~~1 Winters~~ cxl
¾		2 Manton
⅞		1 Winters

FIG. 7.—An NYSE order book from the early 1960s. Source: SEC (1963, pt. 2, p. 491). The prices are in the traditional eighths of a dollar, and the sizes are in round lots of 100 shares. The names are of the NYSE member placing the order, most likely on behalf of an external customer. Orders that are struck through have either been canceled ("cxl") or executed against: for example, three orders to sell at \$35½ have been matched with orders to buy at that price; the member firms responsible for the buy orders are identified by a three-letter acronym.

glimpse its contents on the display screen in the specialist's booth. To those not on the trading floor, however, the full book was invisible: the NYSE distributed externally via the Consolidated Quotation System only the price and aggregate size of the best bid and offer.

Given the extent to which aspects such as this of the status quo of share trading remained intact, it would be easy to conclude that the early 1970s congressional-SEC hinge and the resultant reform efforts were simply ineffectual. For two reasons, though, that would be wrong. First, although the SEC was initially very cautious in using the powers granted it by the 1975 Securities Acts Amendments, in the 1990s and 2000s it did intervene more decisively in how shares were traded, as we shall see in the next section.

Second, the status quo that remained largely unaltered was that of trading itself. The latter's underpinnings—the material processes of transferring the ownership of shares and making the corresponding cash payments (for which see Millo et al. [2005])—were altered, and very consequentially so, although the effects of this took 20 years to become evident. The SEC did implement its 1975 mandate to create a "national system for . . . clearance and settlement," integrating the exchanges' (and Nasdaq's) separate systems into what was to become a single, centralized system, run by a single organization, the Depository Trust & Clearing Corporation. Unlike the fiercely resisted centralization of the glamorous and profitable world of trading, this reform—of what traders saw as "the dreary task of administering back offices" (Seligman 1982, p. 455)—provoked almost no resistance: back offices, after all, were where taken-for-granted clerical work, increasingly by women, took place. However, like the SEC's failure to see the value of having jurisdiction over "pork bellies," the exchanges' failure to resist the centralization of clearing was consequential. In the late 1990s, the new share trading venues discussed in the next section did finally begin to compete effectively with incumbent exchanges. Clearing and settlement were no barrier to them, since with a single centralized clearing system it was easy to buy shares on an incumbent venue and sell them on a new venue, or vice versa. When in the penultimate section we compare the trading of shares to that of futures or Treasury bonds, we will see just how important that was. Certainly, the success of the new venues was to change U.S. share trading utterly.

HFT AND THE TRANSFORMATION OF SHARE TRADING

This section sketches how from 1995 onward the fragmentation of U.S. share trading turned from the latent possibility created by the rejection of the CLOB to an actuality (and therefore into the source of the third of the main classes of HFT signal), with most of that trading taking place within order books that were no longer private but visible to all participants (and thus provided their algorithms with the second class of HFT signal). That history is also the history of how HFT moved from being a peripheral activity to centrality. Starting in the disreputable margins of the U.S. financial system, a hinge between the fields of trading and of exchanges came into being, in which HFT fueled the growth of trading venues that had technological systems that facilitated it, while their growth made HFT an ever more important aspect of the field of trading; the changes in those fields were reinforced by the SEC finally taking decisive action against long-standing sources of structural advantage within them. (The fourth field examined in this article, politics, was less central to these developments than to those discussed in the previous two sections.)

The initial locale of the process described in this section was not the trading of NYSE-listed shares, which continued to be dominated by the NYSE itself until 2005, but shares listed on Nasdaq. During the 1980s and 1990s, Nasdaq trading grew, and new high-technology corporations often chose to list there rather than on the NYSE. Unlike the latter, Nasdaq did not have a trading floor, central order books, or specialists. Rather, each Nasdaq stock had a number of registered market-making firms (the most popular stocks had several dozen). Those firms had a crucial structural advantage. Only they had what Nasdaq called "level 3" electronic access, allowing them to post bids and offers on the screens that displayed Nasdaq's prices. A broker's firm that wanted to buy or to sell at those prices had to telephone a market maker to request to do so, unless it was acting for a retail customer (i.e., a member of the general public) who wanted to buy or sell 1,000 shares or fewer. To save on the costs of handling these small orders manually, Nasdaq had introduced in 1982 an electronic Small Order Execution System (SOES).

During the 1987 crash, many Nasdaq market makers simply stopped responding to SOES orders, and in response the SEC ruled that Nasdaq market makers had to fill orders received via SOES at the prices they were quoting on Nasdaq's screens. Freelance professional or semiprofessional traders—pejoratively dubbed "SOES bandits" by the market makers—soon realized that this gave them the opportunity to pick off bids or offers that market-making firms had not updated quickly enough as market conditions changed. A number of brokerages, often based in run-down buildings in lower Manhattan, created makeshift trading rooms and offered freelance traders access to SOES, either via a trader employed by the brokerage or by placing an order using a computer keyboard and having it fed automatically into SOES. By the mid-1990s, there were as many as 2,000 SOES bandits (Harris and Schultz 1998). At least stereotypically—no demographic data are available—they were often "city college kids from the backwaters of Staten Island, Queens, and the Bronx, the ones who didn't stand a chance at a big bank like Goldman or Morgan" (Patterson 2012, p. 100). Nasdaq's official market makers loathed SOES bandits, sometimes even making death threats against them: "They hated us" (interviewee BW). The market makers persuaded the SEC to prohibit use of SOES by traders deemed to be "professionals," but a number of such traders contested the ban, and in 1993 it was overturned (*William Timpinaro et al. v. Securities and Exchange Commission*, 2 F.3d 453 [U.S. Court of Appeals, 1993]).

From the viewpoint of this article, the most important outcome of SOES banditry was a new electronic trading venue, Island, set up in 1995 by one of the "bandit" brokerages, Datek, and designed to help solve a major problem faced by bandits. (The account of Island in this and the following seven paragraphs is based on interviews with AF, AK, AN, AX, AP, BW, and FA, all of whom worked for Island, and AB, BD, BT, DA, and DE, who traded on it. For more detail on Island's history, see MacKenzie and Pardo Guerra [2014].) Bandits could use SOES to create a promising trading position, but unless they were very lucky, they could not use it to liquidate that position at a profit. To try to do so, they typically had to turn to either Instinet or SelectNet. Although primitive by today's standards, they were electronic systems, but they were also "enemy terrain." Originally designed for institutional investors to trade directly among themselves, Instinet by the late 1980s had become dominated by Nasdaq market makers, while Nasdaq had set up SelectNet so that its member firms, especially its market makers, could trade electronically with each other without paying fees to Instinet.

Originally, therefore, Island simply provided an electronic platform for Datek's bandit customers to trade with each other. Island's central inspiration, programmer Josh Levine, was, however, both an extremely skilled coder and something of an "information libertarian," who—as is clearly evident in electronic records he made available to me—believed that markets and other institutions function best if the actors within them have as much information as possible. Island's technical system, with Levine responsible for the design and much of the code of its initial version, had features that went well beyond the immediate practical needs of SOES bandits. The Island matching engine executed orders in under two milliseconds, which made a transaction look instantaneous to human eyes (by comparison, Instinet's engines took a couple of seconds; interviewee AF).

Levine, who had earlier designed a computer workstation, Watcher, used by Datek's bandit customers, designed Island for direct computer-to-computer interaction. (Previous electronic trading systems such as Instinet had been designed for human use, and automated use of them required clumsy workarounds such as "screen scraping": decoding the stream of binary digits designed to drive a terminal's visual display.) Levine developed two succinct, efficient computer protocols that are now widely used in the fastest forms of automated trading: OUCH, via which bids, offers, and cancellations were encoded for fast, automatic processing by Island's matching engine; and ITCH, which disseminated order book updates, allowing users' computers continuously to synthesize their own mirrors of Island's order book.

Island operated out of Datek's unprepossessing offices on Broad Street in lower Manhattan and was fully automated, with only a handful of staff needed to run it, at least initially. It was therefore able to charge unprecedentedly low fees (a quarter of a cent per share traded) and only for liquidity-taking orders; Island began the practice (now pervasive in U.S. share trading, as noted above) of making "rebate" payments—in Island's case, of a tenth of a cent per share—to liquidity providers (Biais, Bisière, and Spatt 2003, p. 6). Crucially, too, Island's price grid was finer than Nasdaq's. In the mid-1990s, the minimum price increment on Nasdaq (and also, e.g., the NYSE) was an eighth of a dollar, and in practice a tacit agreement among Nasdaq's official market makers to avoid quoting prices in odd eighths of dollars had usually kept the "spread" between the highest bid and lowest offer as big as 25 cents (Christie and Schultz 1994). Island's minimum price increment was 1/256th of a dollar, meaning that it was possible for HFT firms to provide liquidity on Island at prices marginally better than those of Nasdaq's official market makers and still earn very healthy profits.

When Island began operating in 1995, there were only a handful of firms worldwide engaged in anything analogous to today's HFT. Prior to Island, the "fit" between the material practices of these nascent HFT firms and those of existing exchanges was poor (MacKenzie 2017). In particular, automated market making (in which, as described above, a firm's algorithms continuously keep keenly priced offers and slightly lower-priced bids in the order book, constantly changing their prices as market conditions shift) was frustratingly difficult on the NYSE, as interviewee BD reported. As already described, the NYSE's order books were private to its specialists, and NYSE trade executions were not automated: a specialist had to authorize them, usually by pressing "enter" on his computer terminal. Acknowledgment of cancellations of orders—crucial to preventing a market-making algorithm from being picked off—was often delayed for several potentially vital seconds. In addition, the NYSE's fees were high, and even with the late 1990s reduction in the minimum price increment to a sixteenth of a dollar, it was expensive to undercut incumbents' prices.

The technological and economic fit between HFT and Island was much closer: the first clear manifestation of the hinge referred to at the start of this section. As interviewee AB put it, Island had the "first really efficient and scalable cash equities [i.e., shares] matching engine": cancellations and executions were entirely automated and close to instantaneous. As already noted, Island's fees were low, it paid rebates to market makers, and it had a very small minimum price increment. The way in which each individual update to Island's book was disseminated via the ITCH data feed meant that a market-making algorithm could keep constant track of where exactly in the book its orders were and how close they were to execution. Culturally, too, the fit was close: the young tech-savvy men (again, they were nearly all men) who ran Island were similar to those who staffed the nascent HFT firms; indeed, staff circulated between Island and those firms.

Island prospered in good part because it attracted HFT, while HFT gained shape and gathered initial momentum in trading on Island. (Among the HFT practices introduced on Island was colocation, with Island encouraging trading firms to place their servers in its Broad Street building, even in the same room as Island's servers.) When Island was set up in 1995, only the first of the three classes of HFT signal analyzed in this article (futures lead) was fully available to HFT algorithms: Island's order book was visible to them, but it initially formed only a small portion of the market for Nasdaq shares; and there was as yet only limited fragmentation. Futures lead, however, was enough to make HFT on Island highly profitable. In particular, in the late 1990s the CME began to trade a new index future, the "NQ," which tracks the Nasdaq-100 index of shares. Changes in the market for the NQ were a hugely useful signal for trading Nasdaq shares, and especially for market making on Island in the QQQ, an exchange-traded fund, very popular in the dot.com years, that also tracks the Nasdaq-100.

Profits earned on Island helped the new HFT firms to grow, providing capital that enabled them to expand into other markets. Simultaneously, the liquidity they provided helped Island attract ever-larger proportions of the trading of Nasdaq-listed shares. Island's success quickly attracted competing venues with similar "HFT-friendly" features, such as Chicago-based Archipelago; the new trading venues were christened electronic communications networks or ECNs. Year on year, their share of the trading of Nasdaq-listed shares rose inexorably. By March 2000, ECNs had captured 26% of Nasdaq dollar volume; just over a year later (June 2001), that had risen to 37% (Biais et al. 2003, p. 6).

Under its Clinton-appointed chair, Arthur Levitt, the SEC began to use powers granted it by the 1975 Securities Acts Amendments to reduce structural advantages that inhibited competition in share trading. The revelation by the financial economists William Christie and Paul Schultz (1994) that Nasdaq's official market makers tacitly collaborated to keep "spreads" profitably wide sparked nationwide negative publicity, and the emergence of the ECNs gave the SEC a straightforward way of reducing those market makers' structural advantage: it forced them to display ECN prices when they were better than their own (that was the gist of the SEC's Order Handling Rules, which came into force in 1997). The SEC's 1998 Regulation Alternative Trading Systems made it easier to set up ECNs (Castelle et al. 2016), and the SEC also moved U.S. share trading as a whole some of the way toward Island's fine price grid, in 2000–2001 reducing the minimum price increment in U.S. share trading from a sixteenth of a dollar to one cent, a process that market participants called "decimalization."

The NYSE, though, remained protected from the ECNs by the slow ITS. In 2005, however, SEC chair Arthur Donaldson (although a Republican appointed by George W. Bush) broke with his two fellow Republican commissioners and voted with the two Democrats to enact Regulation National Market System (Reg NMS), the current framework governing U.S. share trading (SEC 2005). The Reg NMS stripped the NYSE trading floor of the protection of the ITS: if a price quotation was available only from a human being on a trading floor, it was no longer "protected," and electronic trading no longer needed to pause while an order was routed to that human being.

Just as the ECNs ate into Nasdaq's share of the trading of Nasdaq-listed stocks, so Reg NMS triggered an even more dramatic collapse of the NYSE's share of NYSE-listed stocks. In the five years from 2005, that share fell from 80% to just over 20% (Angel, Harris, and Spatt 2013, p. 20, fig. 2.17). Nasdaq and the NYSE reacted by buying the most threatening ECNs. Island's owner, Datek, had sold it to Mitt Romney's Bain Capital in 2000, which then sold it on to Instinet. By buying Instinet's U.S. business in 2005, Nasdaq thus acquired Island (including the ultrafast matching engine technology that had made it so dangerous a rival), while the NYSE bought Archipelago, also in 2005.[11]

In both cases, though, part of the point of the acquisition was to help the acquirer transform itself materially so as to become more like the ECN it had bought (a process described by interviewees AF, AK, AP, FA, and FB). Nasdaq had already abandoned its traditional telephone-mediated official market-maker way of working in favor of an electronic order book visible to all participants. When Nasdaq bought Island, I was told by interviewee AK, it reengineered its systems around Levine's ITCH and OUCH protocols and an updated version of his ultrafast matching engine. "Island technology runs global equities [share trading] at the moment," said AP in 2012. The NYSE, similarly, in 2002 had made its order books visible to those not on the trading floor (albeit initially with updates only every 10 seconds). When the NYSE acquired Archipelago, it drew on the latter's technology to redesign its systems (interviewee FB). HFT was facilitated by these redesigns, and HFT firms that previously had experienced Nasdaq and the NYSE as unhelpful or even hostile also began to feel courted (interviewee BT).

Decimalization, Reg NMS, and the earlier SEC rulings helpful to the ECNs provided a favorable context for this shift. Those moves by the SEC

[11] Archipelago was renamed NYSE-Arca. Its share of the trading of NYSE-listed stocks alleviated, but did not fully compensate for, the decline in NYSE's share (Angel et al. 2013, p. 20, fig. 2.17).

can be seen as its taking advantage of the emergence of successful rivals to incumbent exchanges to further its long-standing mandate to enhance competition, in a situation in which the balance of forces in the fields of trading and exchanges was far more favorable than in the 1970s. (As interviewee RF puts it, "the ability of the [Securities and Exchange] Commission to move forward on major issues really does require . . . at least some segment of the [finance] industry to be supportive." That segment was too slender at the time of the CLOB controversy; by the late 1990s it was much larger.) The crucial continuing hinge is, however, directly material links between the fields of trading and of exchanges, in which the latter—in their fierce competition for market share—have to provide the technological features (colocation, ultrafast matching engines, etc.) that facilitate HFT, while HFT firms' trading makes the exchanges that most successfully do this attractively liquid venues on which to trade.

While Nasdaq's 2005 acquisition of Island, and the NYSE's of Archipelago, removed two crucial rivals to the incumbent trading venues, other ECNs remained, keeping competition for market share alive. Most important in this respect was a new ECN set up in 2005: BATS (Better Alternative Trading System). It represented a particularly close form of the hinge between the ecologies of trading and exchanges: BATS was set up by a team from the Kansas City HFT firm, Tradebot, with capital supplied in part by another leading HFT firm and two brokerages that specialize in catering to HFT. Like Island a decade earlier, BATS offered lower fees and fast technology (the latter rivaling even Nasdaq's Island-inspired new system). Interviewee EZ reports constant pressure within BATS to speed up its matching engines: "it's . . . Board presentations, quarterly, in terms of how fast the matching engine [is]. Have we cracked the 200 microsecond [barrier]?"

Island led to an informal alliance between a trading venue and HFT; BATS embodied such an alliance in its very creation. However, a hinge, in the sense of Abbott (2005), is not necessarily an alliance, but—as already noted—a process that brings rewards in more than one ecology. There is, for example, no evidence that the SEC intended with 2005's Reg NMS or with its earlier measures to facilitate high-frequency trading. Nor was the SEC in any straightforward sense a supporter of Island, which carried in some eyes an element of stigma ("Those guys are a bunch of crooks": interviewee BD) from its bandit origins.

Similarly, Island was set up not to promote HFT (which scarcely existed in 1995), but primarily to facilitate bandits' manual trading. I could, for example, find no evidence in Levine's documents that his matching-engine design—which gave Island its blistering speed by clever use of "cache" (the limited-capacity but ultrafast memory that is physically part of a processor chip), not slower main memory—had HFT in mind. Rather, it was a programmer's aesthetic, so to speak: an elegantly efficient use of computational resources. Clearly, too, Nasdaq and the NYSE had no intrinsic desire to make changes in the material organization of trading that rendered redundant much of what their specialists, brokers, and market makers did. But, eventually, they simply had to transform themselves to resemble more closely their new HFT-friendly rivals or suffer even more catastrophic loss of market share. No one clearly foresaw or planned to create the current sociomaterial arrangements of U.S. share trading. Rather, these arrangements emerged, and the hinge between the fields of trading and of exchanges (extending, at least partially, to the field of regulation) was central to their emergence.

HFT IN OTHER FINANCIAL INSTRUMENTS

The reader may, nevertheless, worry that how U.S. shares are traded, and the signals that this generates for HFT, might simply be intrinsic to the automation of trading. This section demonstrates that this is not so, by examining briefly the automated trading of three other classes of financial instrument that, like shares, are simple, standardized, and highly liquid: futures, benchmark U.S. Treasurys, and "spot" foreign exchange. (Some HFT firms also trade options and interest rate swaps, but the greater complexity of those products makes them less directly comparable to shares.) Any full treatment is impossible here: this section simply sketches the most important differences between the three markets and share trading, especially in the signals available for HFT (summarized in table 4).

TABLE 4
The Availability of the Three Classes of Signal in HFT Markets

	Signals		
HFT Markets	Futures Lead	Order Book Dynamics	Fragmentation
Shares	Yes	Yes, with partial exception of "dark pools"	Yes
Futures	Not applicable	Yes	No
Benchmark Treasurys	Varies through time	Yes, but many venues have no order books	Yes, but HFTs still excluded from many venues, so limited exploitability
Spot foreign exchange	No	Yes, but many venues have no order books	Yes, but last look and other measures often prevent its exploitation by HFTs

Note.—The availability of the three classes of signal on which this article focuses in the main markets in which HFT firms are active. Source of information is interviewees. A "dark pool" is a trading venue in which the order book is not visible to participants (although its contents can sometimes be inferred by "pinging": repeatedly entering small orders).

Futures: No Fragmentation

By far the sharpest contrast between U.S. share trading and futures trading is that, via the process just described, the former has become fragmented across multiple trading venues (and that fragmentation is the source of a crucial class of signal), while almost all financial futures trading takes place on a single venue, the Chicago Mercantile Exchange. Its market share of all U.S. futures trading in 2015 was 89%, and it is unequivocally dominant in financial futures, hosting, for example, 99.97% of the trading of interest rate futures and options on these futures (Meyer 2015).

Since futures usually "lead" their underlying assets (with the important exceptions mentioned below), that leaves available only one of the three classes of HFT signals on which I have focused, order book dynamics: "futures in general . . . in the most actively traded products, it's all order book dynamics, regardless of what it is you're trading," says interviewee AC. Certainly, HFT interviewees from the futures market seemed focused far more exclusively on the order book than their colleagues in shares were. Spoofing—the entire rationale of which is to "fool" algorithms that make predictions based on the order book—also seemed far more salient to them. In addition, the absence of fragmentation (and the resultant huge single pools of liquidity) in share-index futures trading—the most important such futures, in particular the ES and NQ, are traded only on the CME—may help explain the remarkable longevity of futures lead in share trading.

Why fragmentation in shares and effectively a single exchange in financial futures? Essentially, the conditions that led to the former have been absent in the latter. With no equivalent congressional push for structural reform behind the 1974 amendments to the Commodity Exchange Act, and those allied to existing futures exchanges influencing their drafting, the amendments did not mandate a unified futures clearing and settlement system (which the 1975 Securities Acts Amendments mandated for shares), making it very much harder for new futures venues to challenge incumbents. Nor did the 1974 amendments grant the new futures regulator, the CFTC, the powers to intervene in market structure that the 1975 legislation gave the SEC. In addition, while the SEC is a permanent federal body, the CFTC is dependent on periodic congressional reauthorization, without which (as at the time of writing) it is reliant on year-to-year funding. That, as interviewee RE suggested, leaves the CFTC much less able than the SEC to pursue policies that might generate strong finance industry opposition.

Benchmark Treasurys: Powerful Incumbents, a Bifurcated Market

While U.S. financial futures trading is dominated by a single exchange, Treasurys' trading was—and to a considerable extent still is—dominated by powerful dealers, especially those officially designated by the U.S. Department of the Treasury as Primary Dealers. The market for Treasurys—even for the "benchmark" (most actively traded) Treasurys, which are among the world's most liquid securities—is split into two separate segments: one (to which, for idiosyncratic reasons that cannot be examined here, HFT firms have had access since the early 2000s) in which dealers trade with each other and a second segment (from which HFT is still almost completely excluded) in which dealers trade with their "customers," such as big institutional investors.

Efforts to create for Treasurys trading venues, akin to Island, without fixed "dealer"/"customer" distinctions—venues of the kind now pervasive in shares—have so far failed. Interviewees reported fierce dealer opposition to such venues, and the SEC has not intervened. It is a much weaker presence in Treasurys than in shares. (The ultimate structural difference is that while in most financial markets government agencies are present as regulators, in Treasurys the federal government is itself a market participant, indeed the most important such participant.) Treasurys are exempt from much of the legal framework (e.g., the 1934 Securities Exchange Act and 1975 Securities Acts Amendments) that governs securities trading and gives the SEC its authority. The SEC has to share its limited jurisdiction over the trading of Treasurys with the Department of the Treasury itself and its market agent, the Federal Reserve Bank of New York, both of which have seemed content with the status quo (at least until very recently, as concerns about liquidity have emerged). "It's very hard," says a former SEC official, for the SEC to act "with Treasury Department opposition" (interviewee RF). Among the consequences of split regulation is, for example, that who has responsibility for acting against spoofing in Treasurys has been unclear:

> Author: Who do you go to in the cash bonds [to report spoofing]?
>
> Interviewee BM: The cash you go to no one. No one really covers it.

The fragmentation in the trading of Treasurys is largely not exploitable by high-frequency traders because of their effective exclusion from all but the two main electronic platforms on which dealers trade with each other. Furthermore, the remaining platforms are dealer-customer markets, which mostly do not have central order books with firm bids and offers: rather, trades are initiated by customers sending dealers electronic requests to quote prices to them. Nor is there a straightforward pattern of futures lead: there are periods, interviewees reported, in which the underlying Treasurys lead bond futures rather than vice versa. The most plausible explanation is that very high levels of leverage are possible in Treasurys, because of the long-standing institution of "repo," in which Treasurys are pledged as collateral to guarantee loans to buy them.[12]

[12] Brandt, Kavajecz, and Underwood (2007) find that the cost of repo financing seems to affect whether the bond futures market leads the Treasurys market or vice versa.

Among the factors that have preserved the traditional dealer/customer divide and a bifurcated market in Treasurys is again clearing and settlement. The electronic venues on which Treasurys are traded are not fully fledged exchanges: in the terminology of financial markets, most trading of Treasurys is "over the counter," directly between firms. The largest such firms, including the incumbent Primary Dealer banks, are members of the Fixed Income Clearing Corporation (FICC), but smaller market participants such as HFT firms lack the capital to gain membership of the FICC. Trading venues can face sudden intraday demands from the FICC for multimillion-dollar margin deposits when a bank that is an FICC member trades with an HFT firm that is not. This difficulty proved fatal for a 2015–16 attempt (described by interviewee GF) to create an Island-style venue (open to "dealers," "customers," and HFT firms), which had to be scrapped when the FICC member bank through which it was going to clear pulled out of the project.

Foreign Exchange: "How Is That Legal?"

Similar difficulties have also kept HFT in a relatively weak position in foreign exchange. It too is an over-the-counter market with powerful incumbents. There is an international settlement system, Continuous Linked Settlement, but it does not eliminate all risk of default, so the creditworthiness of the other party to a trade is a pervasive issue in foreign exchange. To operate on any scale in the foreign exchange market, an HFT firm therefore requires the sponsorship of a well-capitalized major bank, and successful trading venues have also needed bank involvement. In the late 1990s and early 2000s, several Island-style trading venues were launched, but all either failed or discovered that they had to "befriend . . . the banks . . . and work with them" rather than try "to force the banks into the new paradigm" (interviewee EN).

Even the weak regulation found in Treasurys has been largely absent: in a world in which, the European Union aside, financial regulation is still mainly national in scope, foreign exchange, an inherently international market, has no regulator with clear authority over it. That has allowed market practices to emerge that have no surviving analogues in shares or futures, in particular "last look," in which a trading venue's matching engines give the servers of a firm granted last look privileges "anywhere from five to ten milliseconds, up to a few hundred milliseconds, sometimes up to a few seconds" (interviewee AT) before consummating a trade. Last look protects market makers, especially banks (whose computer systems are often slow by HFT standards), from having their stale quotes picked off. Interviewee BB, with a background in the trading of shares and futures, reports being incredulous when he first encountered last look: "How is that legal?"

Last look makes what initially were highly profitable HFT liquidity-taking foreign-exchange strategies infeasible: for example, "[triangular arbitrage] doesn't work, because of last look," says interviewee AY.[13] HFT firms that make foreign-exchange profits at the expense of powerful incumbents can also find themselves simply expelled from trading venues: "I got turned off in two days' time because they said we were too predatory" (interviewee BK). The combined result of last look and expulsions, reports FN, has been a sharp decline in the activity of HFT taking algorithms in foreign exchange, a shift also noted by Moore, Schrimpf, and Sushko (2016).

The signals available for HFT in foreign exchange also differ from those in HFT in shares (see table 4). The spot markets in foreign exchange—in which very high levels of leverage are available—generally lead the futures market, interviewees reported, with the effect that signals from Chicago are less crucial. (For example, HFT interviewee BB's firm decided not to pay for the ultraexpensive highest-speed Spread Networks link from Chicago, but only the cheaper Spread service in which strands of cable are coiled to slow transmission by around a millisecond.) Most foreign-exchange trading venues do not have central order books; they rely instead on continuous streams of quotations from market makers, especially big banks, with other market participants relegated to the role of "price takers." With multiple, competing trading venues, there are useful fragmentation signals, but the combination of last look, expulsions, and technical devices that slow trading down limits the ways in which those signals can be exploited.

CONCLUSION

The comparison of the trading of shares with that of other financial instruments reinforces this article's central finding. For all the high-tech glamor of autonomous, algorithmic economic agents, their behavior is—to repeat Martin's apposite phrase—"saturated with history" (2003, p. 44). The "signals" that inform how HFT algorithms trading U.S. shares act and interact are not inherent in the very process of the automation of trading. Three of the four main classes of HFT signal in share trading are the result of conflicts with strong meso-level political economy aspects (conflicts that also, e.g., left consequential legal legacies). There are important differences in the signals available to HFT algorithms trading financial instruments other than shares, differences that are related to the different political economies of those markets. In the briefest of summaries, how HFT algorithms act and interact is a specific, contingent product of the interaction of people, orga-

[13] Triangular arbitrage is the exploitation of fleetingly inconsistent patterns of prices in which, e.g., it is profitable to exchange dollars for yen, yen for euros, and then euros back into dollars.

nizations, algorithms, and machines—not just their current but also their past interaction.[14]

Most likely, the three classes of signal on which I have focused inform the actions of at least one of the parties to the majority of transactions in U.S. shares.[15] To the extent that this is so, what we have found confirms, for example, Krippner's argument that "congealed into every market exchange is a history of struggle and contestation" (2001, p. 785). We have, however, also discovered the importance of what was not struggled over: in particular, the unglamorous activities of clearing and settlement, the "dreary" but deeply consequential material process that underpins financial trading. Furthermore, among the forms of "congealment" revealed here is a crucial mechanism to which economic sociology has not given enough attention: the way in which the outcomes of struggles can condense into material form, into the features of technological systems. Futures lead, order book dynamics, and fragmentation involve issues of law and of political economy, but they are now also material: "hardwired" into the huge, tightly coupled technological system that U.S. share trading has become.

This article therefore suggests that the sociological analysis of HFT—and, perhaps more generally, of today's algorithmic economic life[16]—requires integrating the materialism of actor-network theory (and of the sociology of technology more widely) with economic sociology's, particularly field-theoretic economic sociology's, sensitivity to conflict and to matters of political economy, structural advantage, the law, and government. Consider, for example, the sharpest recent conflict concerning how U.S. shares should be traded, which took place in 2015–16. Its focus was a 60-kilometer coil of fiber-optic cable installed by the new stock exchange, the Investors Exchange (IEX), in the NY4 data center. All orders to IEX and market data from IEX have to pass through the coil, delaying them by 350 microseconds. It was fiercely, albeit eventually unsuccessfully, argued that IEX's installation of the coil should deny IEX orders Reg NMS protection from trade-

[14] I am extremely grateful to one of *AJS*'s referees for remarks that led me to the formulation in this sentence.

[15] With an HFT share of trading of around 50%, it is probable that in the majority of transactions at least one party is an HFT algorithm (since of course there are two parties to each transaction). Furthermore, as interviewee DH told me, many execution algorithms also now use the same classes of signal as HFT algorithms.

[16] Space constraints prevent discussion of the generalizability of this article's findings. Let me, however, briefly say that when algorithms interact primarily with slow human beings (as they do, e.g., in search, in recommendation systems, and in much e-commerce), the specifically Einsteinian materiality discussed here is less evident. Increasingly, though, direct algorithm-to-algorithm economic interaction is becoming more prevalent, and I would anticipate Einsteinian features emerging in other areas in which that interaction takes a form in which speed gives an advantage.

throughs and indeed should prevent the SEC registering IEX as an exchange. Both law and political economy were condensed into that conflict (ultimately, it touched on what the purposes of share trading should be), but at its core was IEX's creation of a material device that deliberately reconfigured at least a small part of the technological system of U.S. share trading (a system that, this article has argued, has emerged rather than having been consciously designed).[17]

Had space permitted, much more could have been said about the influences on the interaction of HFT algorithms trading U.S. shares. The article has focused on the "signals" employed by these algorithms, which are affordances; it has said little about the constraints on how algorithms can act. A similar analysis of those constraints would, however, be possible. They too are both material and the results of struggle, in some cases the same struggles as analyzed above. In the case of U.S. share trading, for example, the most immediate constraints are Reg NMS's order protection rules, which, inter alia, inherit the Intermarket Trading System's ban on trade-throughs. The rules of Reg NMS are also now hardwired into exchanges' and dark pools' matching engines; they have given rise to a staggering variety of types of electronic order—no longer just simple bids and offers—that exchanges make available to help HFT firms make markets profitably within the constraints of these rules.[18] Materially, Reg NMS is Newtonian, so to speak: the rules that constrain today's U.S. share trading are formulated in terms of the best currently available price nationally, when in the Einsteinian materiality of speed-of-light signaling and microsecond response times that current best price depends on something not even mentioned in Reg NMS, an algorithm's precise spatial location.

Other aspects of my treatment of how algorithms interact have also had to be very brief. In particular, there has not been space to explore in any depth the divide in HFT between "making" and "taking," a divide that is simultaneously material/cognitive and cultural/legitimatory. The article has

[17] Readers of Lewis's *Flash Boys* (2014) might form the impression that IEX is anti-HFT, but that is not so. As interviewees told me, HFT market makers are welcome and active on IEX. The chief point of the coil is to make it impossible to profit from the sixth class of signal listed in table 1, in which orders are being matched at the midpoint of the highest bid and lowest offer, but the prices being used to calculate that midpoint are stale (much trading on IEX takes the form of midpoint matching). The data feeds from the other exchanges that IEX uses to calculate the midpoint of the national best bid and offer do not go through the coil (and thus are not delayed), but orders to IEX are delayed. By the time an order attempting to exploit a stale midpoint would arrive at IEX, the prices used to calculate the midpoint would thus already have been updated.

[18] Mackintosh (2014) counts 133 distinct types of order offered by U.S. stock exchanges, but these can often be combined together, creating a much larger universe of composite orders.

also had to be cursory in its consideration of financial instruments other than shares and has said nothing about HFT outside of the United States. As HFT diffused from U.S. share trading to those other instruments, and from the United States to Europe, Asia, and Latin America, it has acted somewhat like a tracer dye: it has flowed easily into some markets, into only specific sectors of others, and not at all into others yet again.

Although the making/taking divide and the wider flow of HFT's tracer dye must be left for future publications, the overall form that the analysis of them must take is now clear. The algorithmic practices of HFT, how those practices are adapted to different markets, how they alter those markets, and whether or not they are successful—all of these are the result not simply of HFT's technological characteristics, but of how those characteristics interweave with the episodes of cooperation and conflict that give markets their form. Those episodes have always involved human beings, and they still do. It is, however, becoming ever more evident that at their core are relations not just among those humans, but also among algorithms and among machines.

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